Risk-Informing Decisions about High-Level Nuclear Waste Repositories

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ABSTRACT

Performance assessments (PAs) are important sources of information for societal decisions in high-level radioactive waste (HLW) management, particularly in evaluating safety cases for proposed HLW repository development. Assessing risk from geologic repositories for HLW poses a significant challenge due to the uncertainties in modeling complex systems of such large temporal and spatial scales. Because of the extensive uncertainties, a typical safety case for a proposed HLW repository is comprised of PA results coupled with various defense-in-depth elements, such as the multi-barrier requirement for repository design, and insights from supplementary analyses. This thesis proposes an additional supplementary analysis, the Strategic Partitioning of Assumption Ranges and Consequences (SPARC), that could be used: (1) in a safety case to help build confidence in a repository system, (2) to provide risk information for decisions on how to allocate resources for future research, and (3) to provide risk information for stakeholder deliberation. The SPARC method extracts risk information from existing PAs and supporting databases by uncovering what sets of model parameter values taken together could result in a substantially-increased-dose (SID) from the repository, and displays the results in SPARC trees. The SPARC method is applied to the proposed Yucca Mountain HLW repository (YMR), as a demonstrative example. The YMR is a particularly interesting example since there have been many public disagreements about it from the inception of the project. This thesis demonstrates how risk information could be extracted from existing PAs for the YMR, with particular attention to addressing the concerns raised by stakeholders. Preliminary application of the SPARC method to the YMR shows that it yields interesting insights into 'savior' attributes of the repository, i.e., those parameter assumption ranges that, if true, are projected to prevent SIDs to different dose receptors (at 10-km or 20-km from the repository, for different future time periods) with very high probability. The thesis also explores how the SPARC method could contribute to other confidence-building exercises, such as assessing repository barrier capability and prioritizing future research efforts.

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Chapter 1. Introduction

Assessing risk from geologic repositories for high-level radioactive waste[1] (HLW) poses a unique challenge because of the temporal and spatial scales involved. The waste remains potentially harmful for time periods on the order of 10^7 years[2]. The repository systems typically involve multiple engineered barriers and emplacement in a remote geologic location. Unfortunately, it is not feasible to conduct experiments on the large temporal and spatial scales of the repository system. As a result, scientists must rely on inference from short-term, controlled laboratory and field experiments, as well as historical data from natural analogs to model the system. This leads to extensive uncertainties in modeling the risk from the repository.

The importance of these extensive uncertainties depends on the context for conducting and using the risk assessments. The U.S. National Research Council (NRC) has pointed out that "safety is in part a social judgment, not just a technical one," [NRC, 1992] and that the proper role of risk assessments is to inform societal decisions and facilitate deliberation among stakeholders [NRC, 1996]. In the case of HLW management, examples of these societal decisions include: (1) whether to reprocess spent nuclear fuel; (2) whether to dispose of the HLW permanently or keep it in monitored retrievable storage; (3) defining what level of risk is acceptable for a storage or disposal facility; and (4) where and how to store the waste in the short- and long-terms. In the

[1] HLW includes spent nuclear fuel, some of the waste streams from reprocessed spent fuel, and some defense nuclear waste. The OECD's definition is: "High-level radioactive waste (HLW) refers to the highly radioactive waste requiring shielding and permanent isolation from man's environment" in [NEA, 2004a].

[2] See dose projections for hypothetical repositories in different geologic media presented in Figures 1-4 in benchmarking study sponsored by the Commission of the European Communities [Cadelli et al. 1988]. Peak doses are projected to arrive $\sim 10^7$ years after closure for the clay repository in Belgium, $\sim 4\times10^6$ years for granite repository in France; in most cases, even if the peak dose occurs earlier, the relative doses remain significant past 10^7 after closure. The main contributor to these long-term doses is Np-237, which has a half-life of 2 million years and experiences significant ingrowth from Am-241, which in turn with Pu-240 in the proposed US spent fuel direct disposal plans account for about half of the radionuclide inventory at the time of closure [McCartin, 2003].

case of HLW repositories, the most important sources of risk information for these decisions are the results of the repository system modeling compiled in a performance assessment (PA). PA is defined by the OECD's Nuclear Energy Agency as [NEA, 1997, p. 40]:

> Quantitative analysis of at least some subset of processes relevant to the behavior of the disposal system and calculation of (at least) intermediate parameters of interest, e.g., thermal evolution, container life time, contaminant release from some subpart of the disposal system. In addition, comparison of intermediate parameters to appropriate criteria set by regulation or design targets, e.g. maximum allowable temperatures, minimum groundwater travel time, contaminant release from a subsystem.

PA is defined in the US regulations (for the proposed Yucca Mountain HLW repository) as an analysis that [10 CFR § 63.2]:

> (1) Identifies the features, events, processes (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal;
> (2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system; and
> (3) Estimates the dose incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence.

PAs inform critical decisions for national HLW repository programs. For example, the repository developer in the US, the US Department of Energy (USDOE), uses PAs to help guide design and programmatic choices. The regulator, the US Nuclear Regulatory Commission (USNRC), uses PAs in its ongoing regulatory activities, such as the prioritization of technical issues, and eventually the licensing decision. The USDOE's total-system performance assessment (TSPA) and supporting analyses will serve as the main sources of risk information for demonstrating compliance with regulatory criteria in its safety case arguing for a license. In addition, public stakeholders will be involved in debates during the repository licensing hearings, and the PAs carried out by the USDOE and USNRC, along with their supplementary analyses will be important sources of risk information for these public debates.

The OECD Nuclear Energy Agency (NEA) has defined a *safety case* as follows: "A safety case is a collection of arguments, at a given stage of repository development, in support of the long-term safety of the repository. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages" [NEA, 1999]. The idea of the safety case is echoed in guidance from expert advisory bodies such as the US federal government's Nuclear Waste Technical Review Board (NWTRB)'s recommendations for "multiple lines of evidence," with PA results serving as one line of evidence [NWTRB, 2000]. Scholars have also noted that the main purpose of a PA is to serve as a tool for making arguments ("rather than absolute truth statements" [Watson, 1994]), thus contributing to the risk discourse among stakeholders [Jenkins-Smith and Silva, 1998]. According to the NEA's view of a safety case as "a collection of arguments" and "a statement of confidence", and the view of PAs as *reasoning* tools, supplementary analyses should call out the supporting evidence for the PA results.

In summary, it is important that the PAs and supplementary analyses in a safety case provide risk information that is relevant for: (1) the developer's programmatic decisions, (2) the regulator's regulatory decisions, and (3) the building of societal consensus and confidence during stakeholder deliberations. These needs imply that the risk results should reflect societal concerns, and should provide specific and detailed arguments of how the repository may fail (i.e., produce undesirable radiation doses to people in the future) or succeed and why the failure scenarios are highly unlikely.

1.1 Uncertainty and Incompleteness

There is good reason to ask, "what if the risk assessments are wrong?". Past experience has shown that risk assessments are often incomplete. One dramatic example was the eruption of the Mt. St. Helens volcano on May 18, 1980; Figure 1.1 shows Mt. St. Helens before and after the eruption. This volcano had been studied by top vulcanologists for a long time. Yet the eruption's magnitude (which was equivalent to the force of a 24 MT bomb), the direction (sideways instead of upwards), and the consequences (e.g., complete decimation of everything nearby) stunned the entire scientific community. None of the vulcanologists and/or seismologists had foreseen that the triggering earthquake could have interacted with the volcano in such a way as to produce such an outcome[3]. A less dramatic but significant example is the performance of the Maxey Flats low-level nuclear waste disposal facility in Kentucky. Risks assessors had projected (in the 1960s) that it would take 24,000 years for plutonium to migrate one-half inch; in reality, the plutonium migrated two miles offsite in less than ten years [Shrader-Frechette, 1993; Polzer et al., 1982]. There have been many other instances in which actual outcomes did not conform to prior assessments.

One of the central questions of this thesis is, given incompleteness in our risk assessments, how can we increase confidence in the decisions we make for HLW repositories? Traditionally, high-risk industries have used a variety of strategies to deal with unforeseen challenges to the system; these strategies are typically called *defense-in-depth.* One popular defense-in-depth strategy is multiple redundant safety barriers incorporated into the physical structure of the system. This is a common strategy for containment of noxious materials from the accessible environment[4]; recall in the 1989 Exxon Valdez spill one of the post-accident criticisms was that the tanker had a single hull and hence only one barrier between the oil and the sea in case of an accident. More recently, scholars have argued [Sorensen et al., 1999] that a second general approach to defense-in-depth, the *rationalist* approach, can be as effective as *structuralist* approaches that concentrate on structural safety elements (such as multiple redundant barriers). In the rationalist approach, any analyses and activities that build confidence in safety are

[3] See [Pringle, 1990] for a summary of lessons learned from the Mt. St. Helens eruption.
[4] "Accessible" to humans, flora, fauna, and any environmental resources we want to protect.

considered elements of defense-in-depth. This approach is particularly useful in recent activities in the nuclear power industry in the US where better information from risk assessments is used increasingly in safety-critical decisions with the purpose of using limited resources more effectively in maintaining (or enhancing) safety [USNRC, 1998]. In this thesis, we build on ideas used for rationalist-style defense-in-depth with risk information for nuclear power plants, and adapt them to HLW repositories for confidence-building exercises.

1.2 Societal Disagreements

Because of the uncertainty in HLW repository risk assessments and differing societal values, there are significant disagreements about many of the world's proposed HLW disposal programs and potential repository host sites where they have been proposed. These societal disagreements are another challenge to making decisions about HLW repositories. In the case of the proposed Yucca Mountain HLW Repository (YMR), the state of Nevada (the host community), public interest groups, peer review boards, and independent scientists[5] have raised numerous *technical concerns* about future YMR performance that they would like resolved. At the same time, the YMR project is operating with limited resources. The repository developer simply does not have the time and capital to address *all* possible uncertainties and concerns.

In addition, some stakeholders have concerns about the *decision-making processes* used for the YMR to date [State of Nevada, 2002], and the state of Nevada has expressed a loss of trust in the repository developer, the USDOE. A recent survey of Nevada citizens shows that: (1) 65% favor continuing opposition to the project and rejecting any negotiations with the federal government for benefits in exchange for going along with the project, and (2) 64% do not trust

[5] For example, see [Makhijani and Saleska, 1992; Shrader-Frechette, 1993; Ewing et al., 1999; Guinn, 2002; IAEA/NEA, 2002; Macfarlane, 2003].

the USDOE to live up to any deal it makes with the state of Nevada anyway[6]. While trust is difficult to gain back once lost, the process of developing the YMR and building the safety case provides an opportunity to demonstrate credibility and build trust.

In high-profile cases that involve a multitude of stakeholders and a complex hazardous facility like the YMR, it is important to have informed and timely debates and use available resources efficiently. Another central question of this thesis is, how can we use information from existing risk assessments to help resolve some of the disagreements over HLW repositories like the YMR, and to help prioritize the use of resources for future research? Since there is extensive documentation on what concerns YMR stakeholders, we can explore what information can be extracted from YMR PAs to inform public discourse that is more productive in resolving disagreements and building consensus on what decisions are acceptable. The existing regulatory compliance criterion for the YMR is in terms of the mean risk projected by the USDOE's PA, but there are numerous reasons to consider scenarios of risk more broadly:

(1) The regulator and other stakeholders are interested in the *confidence* in the projected mean risk (defense-in-depth).

(2) Societal risk preferences show that in addition to mean risk, the following contribute to disutility: (i) the potential for catastrophic consequences, and (ii) uncertainty in risk assessments.

(3) The YM licensing hearings undoubtedly will broach many issues outside the scope of estimating the mean risk; it would be useful to have more information on risk of interest to stakeholders to inform these debates.

(4) Constructing scenarios of risk, e.g., how specifically the repository can fail, can help determine what future research and other resource investments are most important.

[6] Survey conducted by Northwest Survey and Data Services of Eugene, Oregon, in October 2003, with 5% error margin (http://www.state.nv.us/nucwaste/news2003/pdf/survey2003pr.pdf).

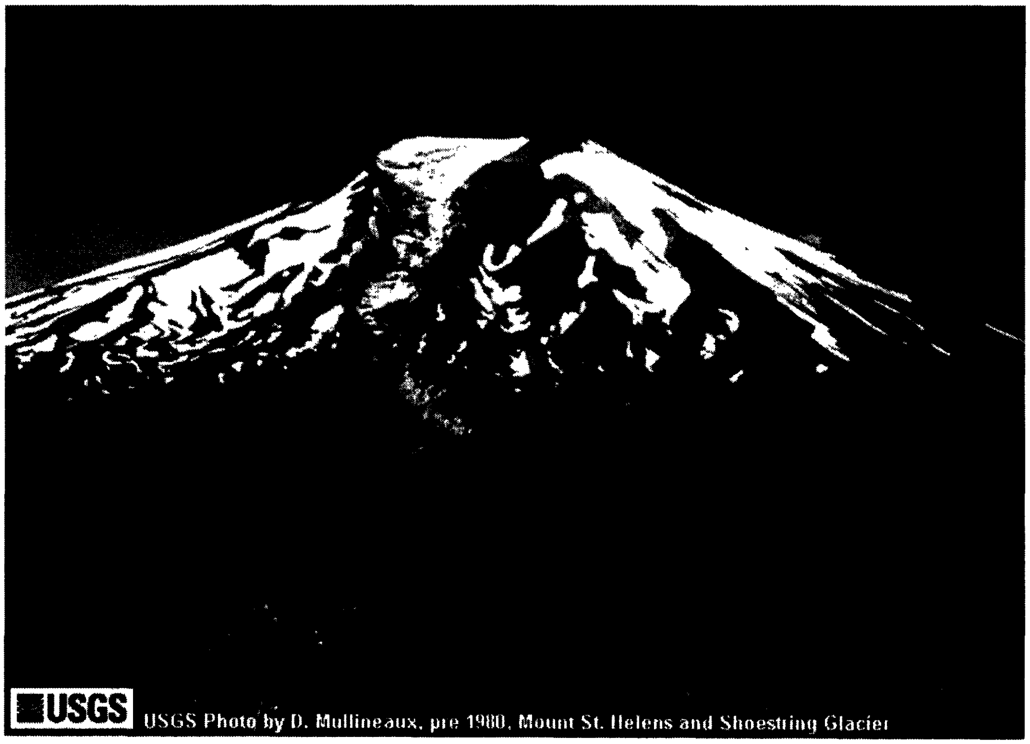
1.3 Thesis Goals and Roadmap

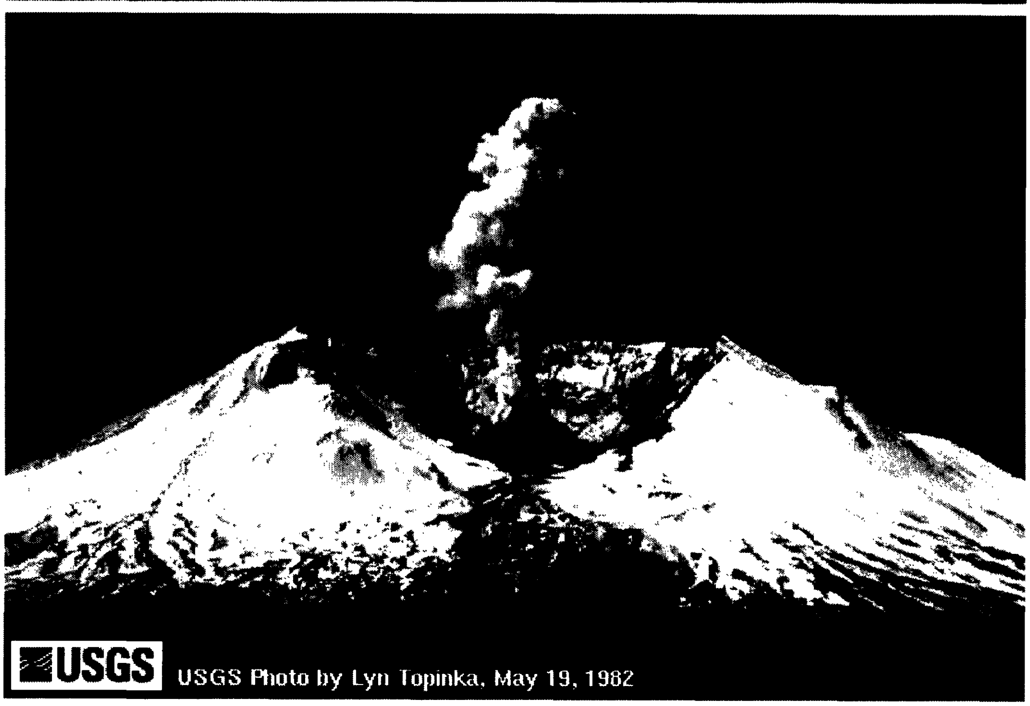
Given incompleteness in risk analyses and disagreements among stakeholders, the questions are (1) how can we collect risk information to increase our confidence in the repository system, and (2) how can we collect risk information to improve the stakeholder dialog on repository risk? At least the first question has been answered partly for nuclear power reactors through the use of system probabilistic risk assessments (PRAs) that show how the system might fail and why the failure probability assessed is so low. To get explanations for potential failures, one can trace all the event-trees and fault-trees that comprise the PRA. But unlike the case of reactors PRAs, there is no summary and explanation of failure scenarios for repository PAs. To get explanations for potential failures, one has to read thousands of pages of supporting documentation on the PAs and sub-models that comprise the overall PA. What's missing is a specific explanation of the PA results of interest, which is precisely what is needed for making good decisions, and informing stakeholder deliberation, about system risk. We want information about how precisely the repository may fail, even if the associated probability is very low, because we want to convince ourselves the probability of these failure scenarios are indeed as low as we think they are. The goal is to find and/or construct failure scenarios that: (1) show specifically how the repository may fail, (2) help identify dominant risk contributors, and (3) serve as the basis for further model uncertainty studies and inform stakeholder deliberation.

The broad goals of the thesis are to develop methodology (and demonstrate its use): (1) to provide risk information in analyses to supplement PAs in a HLW repository safety case, (2) to use risk information for more productive public discourse about HLW repositories, and (3) to explore the evaluation and use of defense-in-depth with risk information for decisions about a HLW repository system. In this thesis, we propose a supplementary analysis that can be used in conjunction with PAs to display these risk results and their underlying reasons more explicitly. We call this method the Strategic Partitioning of Assumption-Ranges and Consequences

(SPARC). The SPARC method is a stylized sensitivity analysis whose results are summarized in SPARC Trees. We begin in chapter 2 with a general discussion of modeling complex systems and the associated uncertainties and present the risk triplet concept, current PA methods and practices, and risk-informed decision-making trends in the US. In chapter 3 we describe the proposed SPARC method, and demonstrate its application by using the Yucca Mountain Repository (YMR) system as an example. In chapter 4, we present an approach to provide risk information of interest to stakeholders, with the objective of improving the public discourse about HLW repositories, and demonstrate how risk information from existing YMR PAs could be used to address stakeholder concerns. In chapter 5, we explore the role of defense-in-depth in *risk-informed integrated decision-making* [USNRC, 2002] for HLW repositories. We conclude in chapter 6 by highlighting the thesis contributions.

Figure 1.1 Mt. St. Helens, Before and After the 1980 Eruption





Chapter 2. Setting the Context

2.1 Modeling the Repository System

In order to estimate the potential adverse consequences of deploying a particular repository system, we have to create a model of this system to project its behavior. A complex system such as a HLW repository is typically decomposed into analytically more manageable subsystems/components, and each of these is modeled in detail; then these sub-models are linked back together to form the overall system model[7] (see [Helton et al., 1997] for an extensive discussion of linked models typically used for PAs.) For each component, we have to (1) determine what output we want from it, which will typically become the input for the next model in the chain-link, (2) create a *model of the world* (MOW; 'world' refers to the system of interest for the particular modeling exercise) that adequately describes the behavior of the component [Apostolakis, 1995], and (3) define the inputs to the model. The MOW is usually a set of mathematical functions that map the vector of input variables, $\boldsymbol{x}$, onto the vector of output variables of interest, $\boldsymbol{y}$, conditional on a set of assumptions, $\boldsymbol{M}$, and a vector of model parameter values, $\boldsymbol{\theta}$, as in Figure 2.1. A simple example of a MOW is the exponential decay equation that determines the quantity of a radionuclide surviving to at least a time t:

$$N(t) = N_0 e^{-\lambda t} \qquad (1)$$

[7] Of course this decomposition is not unique; there are always multiple ways to break down the modeling problem and the particular path is chosen to fit the purpose and limitations of the modeling exercise. For example, the system may be decomposed according to subject-matter expertise and/or existing modeling software for the practical reason of using the available analytical resources in the modeling organization.

There is one input variable, the initial quantity of the radionuclide, N_0. There is one output variable, N(t), the quantity of the radionuclide remaining at time t. The MOW is: (1) the radionuclide decays exponentially (i.e., at a constant rate), assumption M_1, and (2) there is one model parameter $\theta_1 = \lambda$, the decay constant.

2.2 Uncertainties

In most cases, there are significant uncertainties in the analysis, which we can characterize as aleatory and epistemic uncertainties[8] [Apostolakis, 1995]. *Aleatory* uncertainty refers to observable chance phenomena such as the outcome of a coin toss. *Epistemic* uncertainty refers to uncertainty due to limitations in our state-of-knowledge about the system of interest. Epistemic uncertainty can be further categorized into (1) *parameter uncertainty*, the uncertainty in the values of model parameters such as λ in eqn. 1, and (2) *model uncertainty*, the uncertainty in the structure of the conceptual model itself, i.e., the functional mapping in the MOW (such as the equation for radioactive decay above), the uncertainty from not knowing which functional form best describes the system of interest. The most difficult part of model uncertainty is *incompleteness*, our inability to fully characterize the system, i.e., when we don't know what we don't know.

There are commonly accepted probabilistic methods to treat some of the types of uncertainties. The aleatory uncertainty can be represented in the model, e.g., the Poisson model can be used to characterize the aleatory nature of earthquake occurrences. Referring to the example from radioactive decay, suppose that we have only one radioactive atom and we wish to

[8] Strictly speaking, there is only one kind of uncertainty, that due to lack of knowledge. The distinction between aleatory and epistemic uncertainties can be viewed as a decomposition of the fundamental concept of uncertainty that is done for modeling and communication purposes [Winkler, 1996]. The interpretation of the concept of probability that we have adopted is that of degree of belief [de Finetti, 1974], i.e., (1) there is no need for "identical" trials as in the relative frequency interpretation, (2) $P(A)<P(B)$ simply means that the assessor judges B to be more likely than A. This interpretation of probability is the cornerstone of Bayes' theorem.

calculate the probability that it survives at least to a time, t. The aleatory model is the radioactive decay model in eqn. 1, with time, t, as the random variable, so that:

$$\Pr[\text{the atom survives for time at least t}] = e^{-\lambda t} \tag{2}$$

A common method for treating parameter uncertainty is to assign a distribution (probability density function, pdf) to the possible values for each uncertain parameter, e.g., $\pi(\lambda)$ in the radioactive decay model above[9], and then sample these distributions in the Monte Carlo simulation (MCS) in the overall Probabilistic Risk Assessment (PRA) or PA to produce a distribution of outputs. There is no analogous method commonly applied to treat model uncertainty. Various methods have been proposed in the literature (summarized in [Ghosh and Apostolakis, 2002]). Two models for model uncertainty that are combined with expert opinions are presented in [Zio and Apostolakis, 1996]. One approach is to assign weights to the competing model structures and sample these along with the other uncertain parameters in the MCS. But more often, the structural model uncertainty is treated outside the overall PRA/PA, as discussed later.

2.3 DEFINITION OF RISK AS THE RISK-TRIPLET

There are several definitions of *risk* in the literature. One common definition is that risk is the expected consequence of a set of scenarios, i.e., the risk, R, for all possible N scenarios, Si, with associated probability, pSi, and associated consequence, cSi, is:

$$R = \sum_{i=1}^{N} pSi*cSi \tag{3}$$

[9] We note that, in the case of radioactive decay, the numerical value of the decay constant is known with high precision and the pdf $\pi(\lambda)$ is nearly a delta function. This means that the epistemic uncertainty is negligible in this case.

Kaplan and Garrick introduced another definition [Kaplan and Garrick, 1981], known as the *risk triplet*, which is the definition now used widely in modeling risk from nuclear systems. In this formulation, risk is the answer to a set of three linked questions: (1) what can happen? (2) how likely is it to happen (what is the probability of occurrence)? and (3) if it does happen, what are the consequences? The main difference between the expected-consequence and the triplet definitions is that the triplet definition requires explicitly showing the full spectrum of answers to all three questions while the expected-consequence definition collapses the answers into one number; the triplet representation of risk systematically includes uncertainty in the quantification *and* representation of risk. The risk triplet concept was the one used in the USDOE's PAs for the Waste Isolation Pilot Plant (WIPP, the US repository for transuranic waste) regulatory compliance certification application to the US Environmental Protection Agency (USEPA) [USDOE, 1996]. Using the risk triplet definition is a better representation of risk because it comes closer to explicitly showing what stakeholders care about. The definition of risk as the expected consequence is not the most comprehensive definition because: (1) it equates a low-probability, high-damage scenario with a high-probability, low-damage scenario if their respective *expected* consequences are the same; and (2) it does not adequately represent the full spectrum of uncertainty. Studies have shown that members of the public incorporate information about possible catastrophes, i.e., high-consequence, low-probability events, in their risk valuation (e.g., see [Slovic et al., 1980]), and this information about the spectrum of uncertainty is lost when risk is collapsed into an expected consequence value.

The first question in the risk triplet is answered by formulating a set of possible scenarios, Si; the second question is answered by assessing the probability for each of these scenarios, pSi; and the third question is answered by evaluating the consequences of these scenarios, cSi. The scenarios Si can be ordered by increasing associated consequence, cSi, and the cumulative probability of exceeding different levels of consequence can be constructed (as shown in [Kaplan and Garrick, 1981].) In this way, the WIPP PA authors translated the triplet questions into a complementary cumulative distribution function (CCDF). This CCDF has come to be called a *risk curve.*

This risk curve represents the aleatory uncertainty that stems from not knowing which of the scenarios Si will actually occur in the future. For example, will the system evolve in the "normal" way? If so, the "base case" scenario will be realized in the future. Or will the system experience disruptive scenarios, such as an igneous intrusion into an underground waste repository? Then a different scenario will be realized in the future. In the WIPP PA, for example, the dominant scenario was future inadvertent human intrusions into the repository, plausible since WIPP is located in a geologic formation of bedded salt, a useful mineral. The aleatory occurrence of future humans drilling into the WIPP repository was modeled as a Poisson process [USDOE, 1996]. But this aleatory uncertainty is not the only uncertainty in the PAs, as discussed above. Each risk curve is generated from mathematical models of the system. And because these mathematical models are limited by our state of knowledge about the system, there is epistemic uncertainty in the parameters and assumptions in the system model(s), e.g., in the WIPP PA, epistemic uncertainty about the adequacy of the Poisson model (assumption, M_i) to describe future human intrusions, and the epistemic uncertainty in the drilling rate, λ, the Poisson model parameter.

Each risk curve is conditional on a set of parameter values and assumptions ($\boldsymbol{\theta}$ and $\boldsymbol{M}$ in our MOW), and in order to represent risk completely, we must generate a family of risk curves using different sets of parameter values and assumptions sampled from the range of uncertainty. One common way to propagate this epistemic uncertainty is to: (1) assign each uncertain parameter a probability distribution, (2) generate a sample matrix of n vectors where each vector contains one possible set of parameter values and assumptions, (3) run the model n times using the n parameter vectors, and (4) generate an aleatory curve for each of the n parameter vectors (see [Helton et al., 1997] for a more detailed description of this process.) The result is a family of risk curves, an example of which is shown in Figure 2.2. In this simple hypothetical example, we are concerned about possible damage from earthquakes. Suppose that for each earthquake (of a specified magnitude), we suffer $1,000 in damages. We want to know the risk from earthquakes over the next 1,000 years. We model the earthquake occurrence as a Poisson (aleatory) process, so the damage is conditional on how many (k) earthquakes will occur (aleatory scenarios) in the time period of interest, the probability of which is conditional on: (1) the rate of earthquakes, λ, the only parameter in the Poisson distribution, and (2) the assumptions of the Poisson process: $M_1 = \lambda$ is constant; M_2 = events are independent of one another[10]. According to the Poisson distribution:

$$\Pr[\textit{exactly } k \text{ earthquakes occur in } t \text{ years}] = [e^{-\lambda t} * (\lambda t)^k]/k! \tag{3}$$

and the Complementary Cumulative Distribution Function (CCDF) is:

$$\Pr[\textit{at least } k \text{ earthquakes occur in } t \text{ years}] = \sum_{k}^{\infty} \frac{e^{-\lambda t} (\lambda t)^k}{k!} \tag{4}$$

Suppose there is epistemic uncertainty about the value of λ, and we think it is either 10^{-4} per year, 5×10^{-4} per year, or 10^{-3} per year, with equal probability – i.e., the distribution of $\lambda = \{10^{-4}$/yr., probability = 1/3; 5×10^{-4}/yr., prob. = 1/3; 10^{-3}/yr., prob. = 1/3$\}$. Then, for a time period of 1,000 years, we get the family of risk curves shown in Figure 2.2; there are n=3 samples (since there is only one parameter with 3 possible values), producing three CCDF curves that are equally likely to be realized based on our state-of-knowledge.

In the ideal case, for *N* uncertain parameters and structural model assumptions, we would

[10] Assumptions in mathematical terms: the length of time (taken as the random variable) between successive events is independent and identically distributed (iid); the Poisson process of counting events has independent and stationary increments [Ross, 1996].

map an N-dimensional response surface and find the domain of N parameters/assumptions-space where the consequences exceed the desired limit. For a Monte Carlo Simulation (MCS), this would require considering the entire distribution of each uncertain parameter and using every combination of these parameter values to generate all possible risk curves; this would encompass the complete family of risk curves. However, for many practical problems, including PAs for HLW repositories, there are too many parameters with uncertainties to test all the combinations of parameter/assumption values. For example, the USNRC's total-system performance assessment (TPA) 4.1 code for the Yucca Mountain repository has 330 uncertain parameters [CNWRA, 2002]. If we want to test all combinations of 1% intervals of the uncertain parameters, we would have to run the code 100^{330} times. The time to complete one run is on the order of 1 minute. With 5.26×10^5 minutes in a year, it would take a preposterously gargantuan number of computer-years to complete the task. The USDOE's TSPA would require even more time, since it is more complex, with an order of magnitude higher number of uncertain variables and longer computation times.

These practical constraints lead to the use of sampling techniques such as Latin Hypercube Sampling (LHS, as used for the WIPP PA, described in [Helton et al., 1997]) to reduce the burden of computations. The LHS ensures that the full range of each parameter distribution will be sampled and propagated. It does not, however, ensure that all combinations of the different parameter distribution-ranges will be tested, since each parameter distribution interval is only sampled once and propagated with one particular distribution interval from all other parameters. There are smart ways to sample the n-variable domain to reduce the number of samples necessary to establish the parts of the response surface that exceed our performance criterion. But even this is no easy task with a highly non-linear system with hundreds or thousands of variables. And even if we could define the response surface of interest, there would still be incompleteness in our models and variable domains.

2.4 PERFORMANCE ASSESSMENTS AND SENSITIVITY ANALYSES

Ideally, a total-system PA would include all potentially significant uncertainties. As mentioned above, most HLW repository PAs include some uncertainties explicitly; e.g., the MOW parameters, $\boldsymbol{\theta}$, are typically assigned distributions that are sampled and propagated through MCS to a system-performance distribution. The results are represented as a (1) family of risk curves (this was the case for the WIPP, as reported in ([Helton et al., 1997]) and found in the USDOE's WIPP Compliance Certification Application to the USEPA [USDOE, 1996], or (2) represented as multiple possible dose futures and summary measures (as is the case for the YMR PAs, discussed later).

Some of the aleatory uncertainties are addressed through scenario analysis, e.g., by analyzing the effects of random seismic events and the possible consequences of a human intrusion into the repository in the far-future. Unfortunately, other uncertainties, such as many structural model uncertainties (i.e., which structural assumptions $\boldsymbol{M}$ are appropriate for the MOW) are not explicitly propagated through PAs ([Ghosh and Apostolakis, 2002]).

Very often in practice[11], analysts choose a single 'best' model to represent a repository component, and perform individual sensitivity analyses to estimate the impact of different modeling assumptions; then engineering judgment is used to account for model uncertainty, often through a 'conservative' choice in modeling. The problems with applying this approach to uncertainty in the sub-models within a complex PA such as the HLW repository PAs include: (1) It is not easy to determine whether a choice is conservative a priori, given the non-linearity of system response and coupling among sub-models. (2) With hundreds or thousands of uncertain

[11] There are examples of the USDOE's model development process for the proposed Yucca Mountain HLW repository documented at http://www.ocrwm.doe.gov/technical/amr.shtml.

variables and a multi-barrier system, rarely can one variable alone influence the system results significantly. (3) Without some kind of propagation of different model assumptions through the PA, or joint sensitivity analyses, the analyst cannot find those sets of assumptions and parameter values that trip the decision threshold(s) (i.e., the part of the response surface that we care about), which is of great interest to inform the decision problems. At the same time, propagating all possible model uncertainties through the PA is precluded by practical limitations posed by computation time as illustrated above. And, of course, it is not possible to resolve all possible uncertainties because of resource constraints. As PA peer review bodies have noted in the past [Whipple et al., 1999], not all existing information is incorporated into modeling. But there is often yet more information available to consider when modeling a complex uncertain system. It would be useful, therefore, to have some other way to systematically identify *important uncertainties*, i.e., those that may affect the decisions that the PA is informing, such as the prioritization of future research.

There are numerous sensitivity analyses (SA) that are employed for PAs in practice. Different SA techniques are used for different purposes. For example, SA is used as a screening technique to decide what attributes must be included in system modeling because of their importance, and what attributes can be omitted because the system performance (which is what we ultimately care about) is not sensitive to these. We include a brief discussion of some of the methods used to test parameter sensitivity because the insights from these SAs can be incorporated into the SPARC method proposed in this paper. In addition, we will highlight in the conclusions how the insights gained from these SAs differ from those produced by the SPARC method.

Scatter plots are a simple way to detect whether there is a relationship between two variables. When using the results from MCS, values of θ_i for each realization can be plotted against the system outcome of interest to detect patterns. Scatter plots were used extensively in the USDOE analyses for WIPP [Helton et al., 1996].

Another simple SA method is to test the sensitivity of system performance to a particular parameter, component, or process – a θ in our MOW – by varying it and observing the effect on system performance. For LHS/MCS PAs, this can be done by: (1) picking a high, medium, and low value of θ, (2) carrying out the MCS three times with all the other uncertain parameters while keeping θ fixed at the high, medium, and low value in turn, and (3) looking at the effect of the feature of interest on the expected system performance. The USDOE used this method extensively in its uncertainty analyses in support of the Yucca Mountain site recommendation [USDOE, 2002]. *One-off/One-on analyses* for system features (components or processes) are very similar. The difference is that instead of picking low and high values for a particular parameter or component performance, the component is removed completely for a one-off analysis, and inserted (where it didn't exist before) in the one-on analysis. The importance of the component is measured, once again, by the magnitude of the resulting difference in expected system performance. Both the USDOE and USNRC have used one-off/on-on analyses for YMR PAs.

Stepwise regression analysis is another common SA technique. The goal of the analysis is to express the output, y, as a linear equation of the *n* inputs, $\boldsymbol{\theta}$, with the minimum residual sum of squares (minimizing the distance between the known response curve points and the linear approximations for these given $\boldsymbol{\theta}$ value vectors):

$$y = a_1\theta_1 + a_2\theta_2 + a_3\theta_3 + \ldots + a_n\theta_n + b \qquad (5)$$

The search for this equation is done step-wise, i.e., one variable at a time, at each step adding the θ_i that reduces the sum of squares the most. The regression can also be done after a number of transformations, such as log transformations and/or variables normalized by their mean values. Step-wise regression was used in the USNRC SA for parameters in the TPA 4.1 code [Mohanty et al., 2002]. Related analyses include correlation analyses based on rank-transformed variables, i.e., ordering both θ_i and y from smallest to largest respectively, and testing for monotonic relationships. *Partial rank correlation*, *Spearman rank correlation*, and related analyses were used for WIPP and are described extensively in [Kleijnen and Helton, 1999] and [Helton et al., 2000].

The *Kolmogorov-Smirnov* (K-S) test can be used with the results of a MCS to test parameter sensitivities. The MCS realizations can be partitioned into two bins, e.g., grouping the realizations with the highest 10% of consequences together, and the rest together. Then, the K-S test is used to see if the values of θ_i in one bin, and θ_j in the other bin, were drawn from the same theoretical distribution [Mohanty et al., 2002].

Differential analysis (one type of traditional *uncertainty analysis* [Morgan and Henrion, 1990] tests the magnitude of $\delta y/\delta\theta_i$ for small changes in θ_i around its mean value. In the USNRC's SA for parameters in its YMR PA, it used a 10% change in θ_i values and normalized to get a sensitivity coefficient $S_i = (\delta y/\delta\theta_i)*(\theta_i/y)$. In a related SA technique, the *Morris method,* $\delta y/\delta\theta_i$ is treated like a random variable, and sensitivity of y to θ_i is measured by the mean and standard deviation of $\delta y/\delta\theta_i$. A large mean value indicates a large overall influence of θ_i on y, while a large standard deviation is an indicator of a highly nonlinear influence on y, or perhaps significant interactions with other θ_j ([Mohanty et al., 2002]; [Helton and Davis, 2003]).

From the perspective of risk-informed decision-making, the goal is to extract from PAs and SAs the necessary risk information for important decisions in HLW management.

2.5 USE OF RISK INFORMATION

2.5.1 Risk-Informed Decision-Making

In the US, commercial nuclear operations and regulation are using increasingly more risk information for safety-decisions. The goal of this initiative is to improve decisions by making resource allocations commensurate with risk importance, and hence more rational. Risk assessments help identify which system components contribute the most to risk, and risk managers can 'turn up the microscope' [Garrick, 2003] on these risk contributors. The USNRC announced its intention to use more risk information in its regulatory activities in 1995, and published a white paper in 1998 [USNRC, 1998] outlining what information risk assessments should provide.

It is useful to take a look at how risk information is used for nuclear power reactor operations and regulation to understand our analogous goals for HLW repositories. For nuclear power reactors, level-1 probabilistic risk assessments (PRAs) provide scenarios for the pre-defined undesirable *end-state* of reactor core damage and large early release of radioactivity. The risk/failure scenarios analyzed are those that lead to core damage or large early release. Figure 2.3 shows a typical generic event tree for an initiating event that shows how a potential core-damage scenario may evolve. The sequences begin with an initiating event that challenges the system, then each of series of safety systems in the multi-barrier system has a chance to 'save' the system. The undesirable end-state of core damage can only be reached if each of these systems fails, the sequence captured by the lowest branch of the tree. Probabilities/frequencies are assigned to each branch in the event tree, based on experience and expert knowledge.

The risk insights from these analyses are summarized in PRAs. The PRA for a nuclear power plant contains all the known event-trees and supporting fault-trees for core damage events. The relative risk contributions (e.g., percent contribution to core damage frequency) by plant components and subsystems can be calculated by tracing their role in the event/fault trees. This information on the relative risk contributions by different components and sub-systems can be used to prioritize, for example, maintenance and quality assurance activities, and to apply for changes in the licensing basis for individual power reactors (since the licensing bases were often based on deterministic analyses many years ago, before risk information was available), e.g., reducing the inspection frequency for components that are not significant risk contributors while concentrating more resources on components that are.

PAs for the YMR are different in that they model the evolution of the repository system and display the resulting *performance*, as the name indicates. The results show probabilistic performance for all levels (not just undesirable end states), even those that are several orders of magnitude below the performance goals, e.g., the regulatory goal for the YMR is a 15 mrem/yr dose, but most PAs show detailed dose projections into 10^{-12} mrem/yr range. A quantitative *risk* assessment (QRA) for the YMR would concentrate on the scenarios of risk, rather than performance, to better fulfill the USNRC's intentions for risk information and be more useful for decisions. QRAs could supplement the existing PAs for HLW repositories.

In a reactor PRA, if we want to know the reasons for possible system failure, we can trace the sequence of events through the event trees, and similarly trace the ways each event can occur through the underlying fault trees. We seek to provide a similar explanation for PA results by finding failure scenarios for the repository system. But PRA-style fault-trees, event-trees, and scenarios cannot be imported directly for HLW repositories because their system natures are very different. Some of the salient differences are: (1) Reactors are designed not to fail, whereas the repository system is expected to 'fail' eventually, sometime in the distant future; (2) Most basic events in level-1 reactor PRAs are modelled as binary, random failures, whereas repository components degrade in complex, continuous processes in which their performance declines slowly; (3) For HLW repositories, there is no analogous end-state to core-damage for reactors, which simply signifies that the reactor has *failed* to prevent an accident; core damage is a binary end state – the core is either damaged or not. 'Failure' has to be re-defined for repositories where the end state, projected doses to people living near the repository, has continuous possible values and no sharp binary distinction. Because of these three differences, we will re-define what a *scenario* means for HLW repositories, as explained in the next section.

2.5.2 Scenario Definition for HLW Repositories

We can adopt the common definition of a scenario as one collection of possible repository features, events, and processes (FEPs) that will be realized in the repository's future. Furthermore, in the context of gathering risk information, FEPs should be defined strategically to be meaningful from a risk perspective. We will define scenarios for HLW repositories more specifically in terms of a series of strategic partitions. The first strategic partition is for the end-states, the consequences of interest. As mentioned above, nuclear repositories do not *fail* in the way that nuclear reactors do, and hence failure must be redefined. We build on the Generalized Sensitivity Analysis (GSA) tool introduced by Hornberger and Spear [Hornberger and Spear, 1981] for environmental systems. These authors partitioned MCS outcomes based on pre-defined system behavior of interest (in that case, the behavior of interest consisted of key measures of eutrophication in a lake, e.g., dissolved phosphorous concentration, exceeding specified thresholds). MCS realizations producing this behavior was placed in one bin, and those producing non-behavior were placed in another bin. This is an appropriate way to think of partitioning HLW repository PA results as well. For our purpose, the system behavior of interest is delivery of a specified peak dose (or greater) to any individual living near the repository sometime in the future. We will call this behavior *Substantially Increased Dose (SID).* We can define a SID scenario as one collection of FEPs that leads to repository performance that crosses the regulatory goal (a reference point) as defined in the regulations. SID does *not* imply a violation of regulatory criteria, since the regulatory goal is based on expected dose only, i.e., the mean of all the dose projections produced by the PA should lie below a particular value (explained in more detail later).

Next, we have to partition FEPs strategically to create scenarios of risk. In the example application presented in this paper, the PA parameters represented both model parameters and assumptions in the MOWs. For example, some of the PA parameters are parameters in sub-models, such as one of the dominant parameters discussed later, the pre-exponential coefficient, r_O, in the default spent fuel dissolution model [CNWRA, 2002]:

$$r = r_O \exp(-E_a/RT) \tag{6}$$

where E_a is the activation energy, R is the universal gas constant, and T is the waste package temperature. There are other parameters that represent a choice of alternative model structures, M_i; for example, there are two spent fuel dissolution models available in the PA code used in the application: (1) the default model is the bathtub model where spent fuel is immersed in water inside the waste package slowly dissolves; (2) the alternative model is the flow-through model where water contacting spent fuel as it flows inside the waste package is able to dissolve the fuel as it goes. The alternative spent fuel model can be invoked in the PA by toggling a 0/1 parameter in the PA. Yet other PA parameters are *lumped* parameters that can represent different physical processes and modeling assumptions as well. Examples of this are the "Waste Package Flow Multiplication Factor" and "Subarea wet fraction" parameters discussed later. The subarea wet fraction is a parameter that describes what percentage of the soil above the repository is wet. It is a lumped parameter because there are numerous physical processes and modeling assumptions that could lead to different percentages of wetness. For example, when the waste package flow multiplication factor is high at the same time that the subarea wet fraction is low, these parameter value intervals simulate the effects of pre-dominantly fracture flow through a few large fractures in the rock above the repository, whereas the assumption in most cases is that the flow would be predominantly matrix-flow with a small fraction of the flow occurring through fractures.

Thus, our scenarios, which are collections of FEPs that lead to SIDs from the repository, will actually be defined in terms of PA parameter distribution intervals, since the parameter values capture *both* assumptions about the true values of model parameters *and* assumptions about different processes that may be at work in the repository. Figure 2.4 shows a conceptual representation of a scenario constructed in this way. This scenario is a combination of the parameter values in the shaded intervals of their pdf's.

2.5.3 Pertinent Risk Information for HLW Repositories

The USNRC's 1998 white paper states: "a *risk assessment* is a systematic method for addressing the risk triplet as it relates to the performance... to understand *likely outcomes, sensitivities, areas of importance, system interactions,* and *areas of uncertainty.* From this assessment, *important scenarios* can be identified" [USNRC, 1998]. Current PAs do a good job of projecting likely outcomes, but risk assessment areas that could use improvement include sensitivity and importance analyses (from a *risk* perspective), and the identification of important scenarios. In addition, in recent years, advisory bodies and peer-review teams have noted the need for more risk explanation to accompany PAs for the proposed Yucca Mountain Repository. For example, the International Atomic Energy Agency/OECD Nuclear Energy Agency International Review Team (IRT) noted, "the US approach to regulation has focused attention on the presentation of aggregated results that can be compared directly with regulatory requirements. The IRT considers that more intermediate results and disaggregated end results should be given," ([IAEA/NEA, 2002], p. 62)[12]. The same panel also raised the issue of possible *risk dilution* through sampling inappropriately broad parameter distributions that could hide risk; finding and scrutinizing SID scenarios is one way to build a defense against potential risk dilution effects in the aggregated results. The IRT also recommended that the understanding of PA results should be improved, "making use of a range of approaches," including, "Development of an understanding of what extreme conditions might give rise to doses above prescribed regulatory criteria, and a description of the factors that make these situations unlikely," ([IAEA/NEA, 2002],

[12] Some of this type of explanation *was* provided for the WIPP, e.g., in the Compliance Certification Application supporting documentation [USDOE, 1996].

pp. 59-60). In terms of explanations of risk, the USNRC's Advisory Committee on Nuclear Waste (ACNW) has also noted the importance of understanding PA results, stating, "the Committee strongly supports backtracking from the final results of the performance assessment, where few radionuclides dominate the performance, into the internals of the model... the Committee believes this approach will enable the [USNRC] staff to ferret out the contributing factors and basis for their respective contributions" ([ACNW, 2003], p. 6), and commending recent efforts in this direction.

The goal of the method proposed in this paper is to construct a specific explanation of the PA results of interest, which is needed for risk-informed decision-making and risk-informing stakeholder deliberation. We want information about *how* the repository may produce SIDs (in terms of FEPs as described above) even if the associated probability is very low, because we wish to convince ourselves and other stakeholders that the probability of these SID scenarios are indeed as low as we think they are. With the typical sampling algorithms (LHS) used in PAs, these low probability scenarios may not emerge from the MCS, because they are far out on the tail of the system-level performance distribution. Better estimates of the distribution tail are needed because: (1) stakeholders want to know about high consequence-low probability outcomes, not just the mean outcome, and (2) we may be wrong about the low probabilities because of all those things that we know that we left out of the analysis, such as the structural model uncertainties, and we can reassess the probabilities and possible incompleteness after we find which repository attributes are important through the SID scenarios. Therefore, the goal is to find and/or construct SID scenarios that: (1) show specifically how the repository may result in SIDs, (2) help identify dominant risk contributors, and (3) serve as the basis for further model uncertainty studies and inform stakeholder deliberation.

Figure 2.1 Modeling the system of interest requires defining the outputs of interest, y, the required inputs, x, and the functional relationship between x and y defined by the Model of the World.

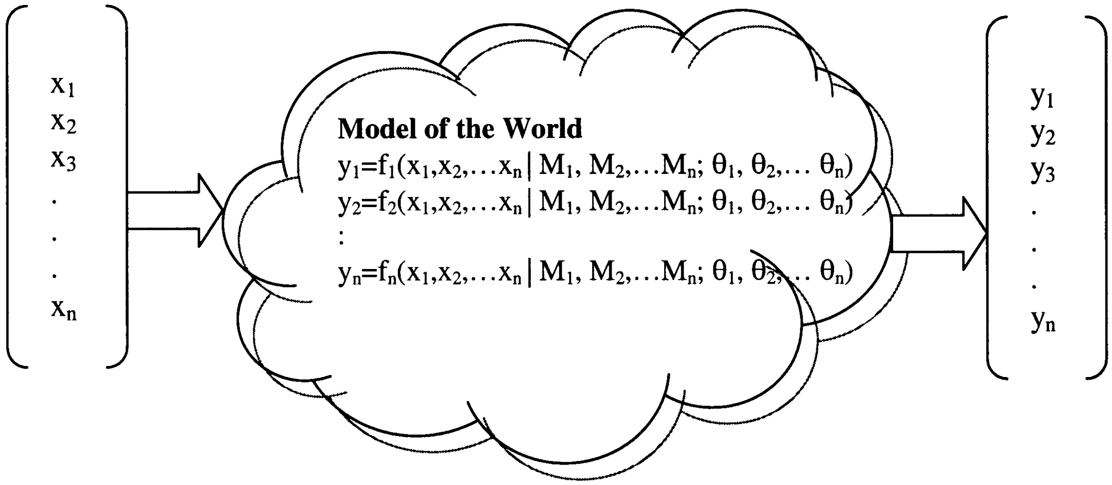


Figure 2.2 Family of risk curves for the hypothetical earthquake damage example.

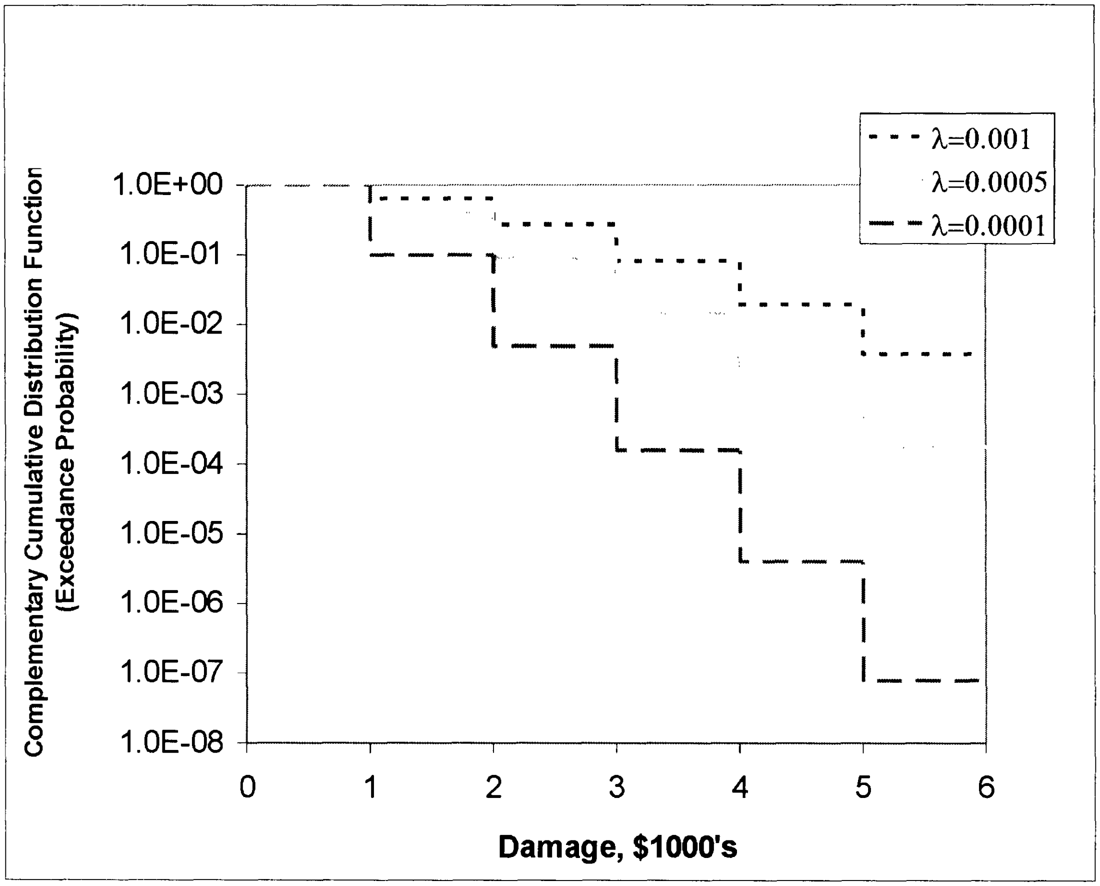


Figure 2.3 Example of a generic nuclear power reactor core-damage event tree

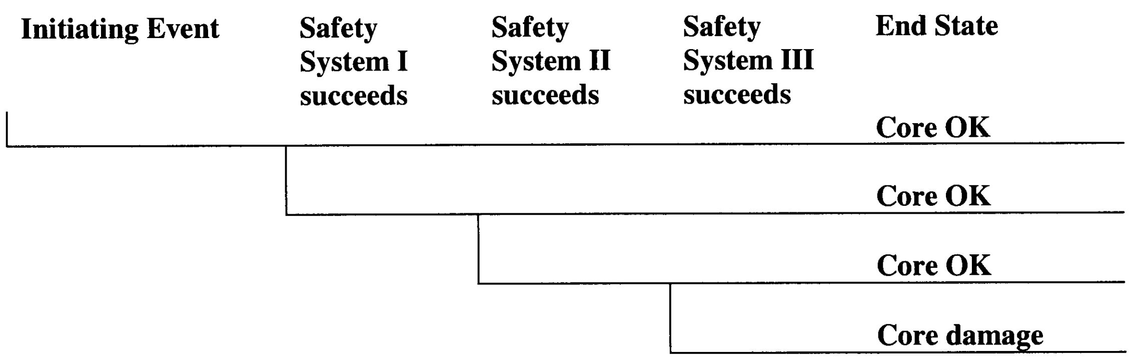
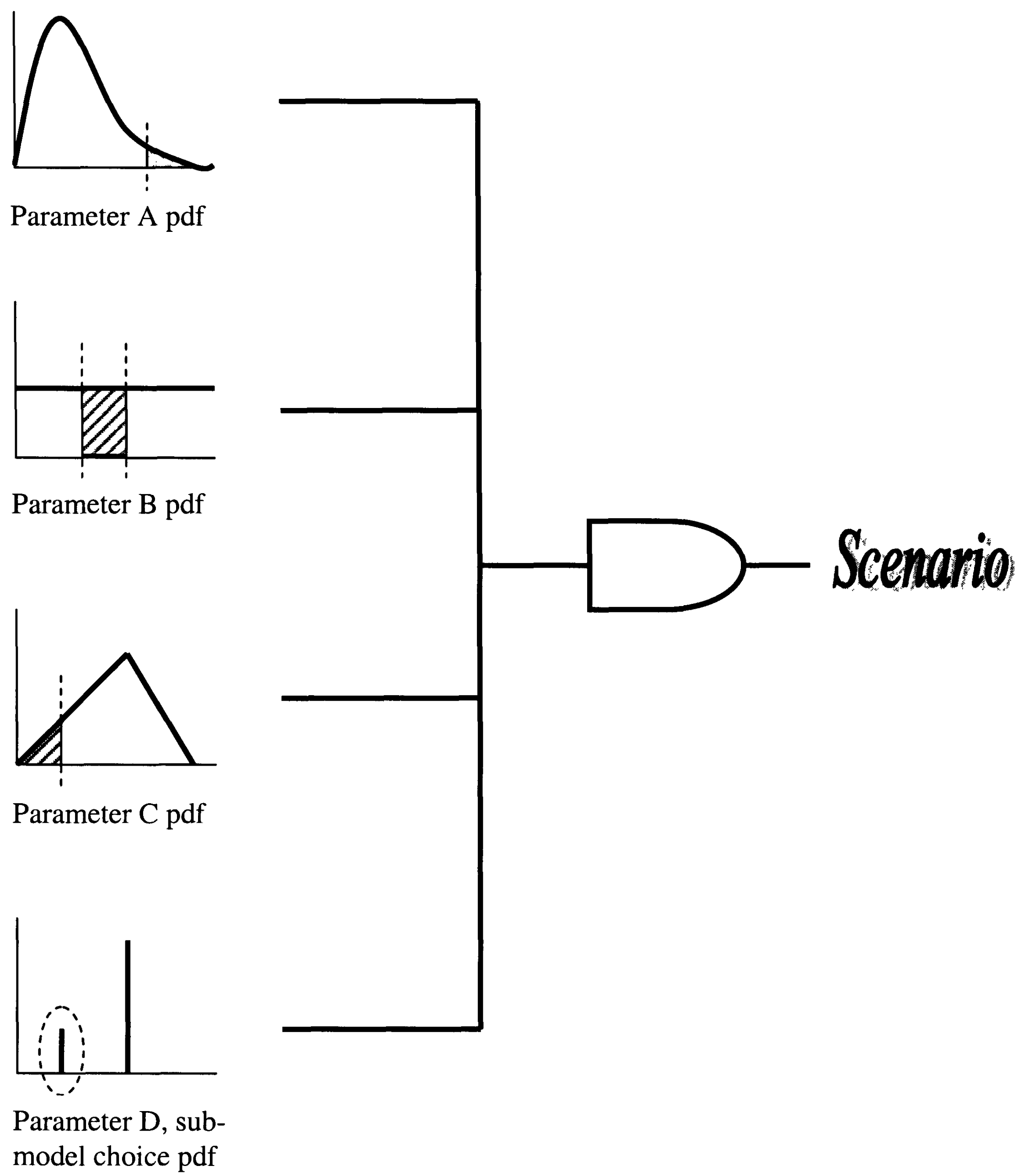


Figure 2.4 A *scenario* is defined as a collection of FEPs which are captured in intervals (shaded regions) of PA parameter distributions



Chapter 3. The Strategic Partitioning of Assumption-Ranges and Consequences Method

3.1 SPARC Trees

In this chapter, we propose the SPARC method, which can help provide risk information for decisions about HLW repositories. This proposed analysis has a two-prong focus: (1) finding SID scenarios and (2) finding 'savior' attributes. The SID scenarios are those combinations of possible FEPs, which are often embodied in parameter value intervals (as explained above), that can lead to individual doses that cross the regulatory threshold. These scenarios tend to be tail scenarios; i.e., if we look at the distribution of outcomes from a typical PA, the very small number (if any) of the individual realizations that cross the decision threshold are on the tail of the distribution. The savior attributes are those combinations of possible FEPs that make it virtually impossible for the repository to lead to SIDs, even when challenged severely.

Note that the US regulatory limit is defined for the mean of the PA results ("reasonable expectation"[13]); we do not propose this supplementary analysis to replace the TSPA projected-mean dose regulatory criterion for the base case (<15 mrem/yr for the first 10,000 yrs, as set by the USEPA in [40 CFR 197]; disruptive scenarios are considered separately). Instead, this analysis would serve a supplementary purpose, to help explain PA results, and focus further analyses and deliberation among stakeholders. The SPARC method comprises the first three steps of a larger analysis that consists of the following iterative steps:

[13] 10CFR§63.311 states, "DOE must demonstrate, using performance assessment, that there is a reasonable expectation that, for 10,000 years following disposal, the reasonably maximally exposed individual receives no more than an annual dose of 0.15 mSv (15 mrem) from releases from the undisturbed Yucca Mountain disposal system." [10 CFR 63]. By "reasonable *expectation*" the USEPA means, and the USNRC and USDOE interpret it to mean, the average of all PA realizations. See discussion in [USNRC, 2001].

(1) Identify important repository attributes.

(2) Find (a) SID scenarios and (b) "savior" attributes.

(3) Explain the reason(s) for SIDs in the SID scenarios, and display results in SPARC trees.

(4) Present supporting evidence for assessing very low probabilities of SID scenarios and probe possible incompleteness in existing analyses.

(5) Identify important uncertainties.

PAs consist of hundreds or thousands of uncertain parameters and processes; not all of the parameters contribute significantly to variations in system-level performance. It is imperative, therefore, to identify the important uncertain attributes so that the scenario explanations can be defined based on these. There are several well-established methods that can be used to find the important attributes; these methods are largely different kinds of sensitivity analyses, as described above (see [Codell et al., 2001] and [Helton and Davis, 2003] for more extensive description of these methods). Since the PAs typically use LHS in conjunction with a MCS, the first order estimate of scenario probability can be derived from the LHS size and associated frequency of the scenarios in the MCS, and the first order estimate of attribute probabilities can be taken from the parameter distributions. The probability estimates can be further refined by scrutinizing the underlying technical evidence supporting the scenarios. The results of these analyses should indicate which uncertainties and repository attributes are the most important from a risk perspective.

3.2 EXAMPLE

3.2.1 Example Application to the Yucca Mountain Repository PA

We illustrate the SPARC method through an example, and touch briefly on the fourth and fifth steps of the larger analysis through a particular case study within the example. We use an older version of the USNRC's total-system performance assessment code for the YM HLW Repository (YMR), TPA 4.1j [CNWRA, 2002] (the dose projections presented here are based on an out-dated database and a code created as a tool to improve understanding of the YMR system, *not* as a compliance demonstration tool.) The actual numbers here are not important; rather, we are trying to demonstrate *how* the approach could be applied.

The YMR is a typical multi-barrier system that provides layers of defense between the biosphere and the radionuclides in the waste. The goal is to provide reliable containment from the accessible environment for some period of time, during which many of the most harmful radionuclides will decay away (such as Cs-137 and Sr-90 with half-lives on the order of 30 years), and then delay the release and transport of the eventually-escaping longer-lived radionuclides to where future people can be exposed. Figures 3.1 and 3.2 (based on [USDOE, 2002]) show schematic diagrams of key components of the repository system. Figure 3.1 shows the general location of the repository tunnels with respect to the mountain above and potential dose receptors living downstream in the future. The proposed repository would be located in tunnels bored approximately 300 m below the ground surface, and approximately 300 m above the present-day groundwater table. The regulatory compliance point for the Reasonably Maximally Exposed Individual (RMEI) is 18 km away from the repository in the predominant direction of groundwater flow.

Figure 3.2 shows a cross-section of a tunnel, called a *drift*, and the main components of the repository on the scale of a drift, in the site recommendation reference design. The main engineered barriers in the site-recommendation reference design are: (1) the waste form, either spent nuclear fuel in fuel assemblies or defense HLW glass; (2) the waste package (WP), the large cylinder in which the waste form would be placed, comprised of corrosion-resistant metal; (3) the metallic drip shield designed to divert water away from dripping on the WP; (4) the concrete invert pedestal on which the WP would rest. This engineered-barrier system would be placed in the repository tunnels, the location of which is shown in Figure 3.1, as "Repository."

There are two main pathways for radionuclides to reach humans in the 'normal' evolution of the repository system: (1) radionuclides that make it to the saturated zone below the repository and travel with the groundwater to potential drinking water wells downstream; or (2) to a much smaller extent, gaseous radionuclides (e.g., C-14, gap inventory in spent fuel) that may escape the engineered barriers and travel upwards through the overlying rock to be released through soil pores into the atmosphere above. The first pathway is the dominant one; water is the main vehicle for radionuclides to get from the waste form to people.

The normal evolution of the repository is the following 'base case' scenario: (a) some of the rain water that infiltrates the mountain will percolate into the repository drifts (shown in Figure 3.2) after the rock surrounding the drifts has cooled down to below the boiling point of water; (b) water entering the drifts then has to penetrate the drip shield, which is like an umbrella for the waste package (WP) and the WP, which is the large cylinder holding the spent fuel and HLW glass, to contact the waste form; (c) water (or humidity) begins dissolving some of the waste form, and some of the radionuclides are released into the available water; (d) this contaminated water then has to exit through another penetration in the WP, get through the invert below (some of the radionuclides are lost to the invert through sorption), and eventually reach the unsaturated rock zone above the water table; (e) contaminated water then drips through connected pores in the unsaturated zone (UZ) to the saturated zone (SZ) below, and in the process, some of the radionuclides are captured by the UZ rock through sorption processes; (f) the contaminated plume then travels with the groundwater, and some of the radionuclides travel with colloids (larger conglomerate particles consisting of invert and/or soil particles), and once again some of the radionuclides are captured through sorption processes in the SZ; (g) some of the radionuclides eventually reach people, since the contaminated groundwater is available to be pumped downstream (as shown in Figure 3.1); people are exposed through drinking groundwater, eating vegetation grown with contaminated irrigation water, or eating animals who are exposed, and so on. The entire process should take at least thousands of years, and more likely would take hundreds of thousands of years.

The repository system is a multi-barrier system where each barrier either delays and/or reduces the release and transport of the radionuclides: (1) the host geologic location in a desert climate limits the availability of water, the main vehicle for release and transport, and is a relatively unattractive place for large populations to inhabit in the future, thus limiting the potential future population exposed; (2) the engineered barriers are designed to contain the radionuclides for long periods of time during which many of the harmful radionuclides will have decayed away; and (3) the UZ and SZ below the repository delay radionuclide transport, and attenuate the concentration of radionuclides reaching the accessible environment through irreversible capture processes such as sorption.

The USNRC's TPA is more flexible in its capability to test different assumptions about the YMR, and because of its relative simplicity, runs in a much shorter time than the USDOE's TSPA. In addition, it contains more lumped parameters that could represent different physical processes, which lends flexibility in testing model sensitivities. It is a good basis for the supplementary analysis proposed here. We will define scenarios in terms of collections of FEPs, and all repository attributes discussed here are embodied in parameters ($\boldsymbol{\theta}$) in the TPA code, though some of these parameters are actually proxies for model assumptions ($\boldsymbol{M}$). When we construct scenarios, we will be looking at collections of parameter-value intervals that represent assumptions (both $\boldsymbol{\theta}$ and $\boldsymbol{M}$) about the repository.

In this older TPA code, the only dose-receptor locations are 10-km or 20-km away from the repository, since the code was developed before the final regulations were promulgated that fixed the hypothetical receptor at 18-km from the repository. It turns out that with the base-case database of uncertain parameter distributions, it is nearly impossible to cross the regulatory criterion of all-pathways dose 15 mrem/yr for the 20-km receptor within the regulatory compliance period of 10,000 years[14]. Since the focus of the SPARC method is to find how the repository may produce SIDs (even with the knowledge that these are highly unlikely scenarios), we use instead the dose from drinking-water only to the 10-km receptor. While this does not match the regulatory criteria, it is nonetheless useful because: (1) we can illustrate the application of the SPARC method because we do observe some SIDs for the 10-km receptor within the first 10,000 years after repository closure; (2) it fits with the general idea of using supplementary 'calculation cases' or testing 'what-if' scenarios (ideas that were recently lauded in the NEA's review [NEA, 2004b] of Swiss PAs), to improve understanding and build confidence in the repository system. We would like to note that looking at doses to the 10-km receptor reduces the contribution of the SZ in delay and capture of radionuclides, compared to the 18-km or 20-km receptor's dose. Hence, if SZ attributes are not implicated as risk contributors (good or bad) in our analysis, it does not mean that they are not important. And as mentioned above, since we are ignoring non-drinking-water doses, potential farming-related risk contributions to the 18-km or 20-km dose receptors will also be missing in the analysis for the 10-km receptor.

1. Identify important repository attributes

We take advantage of the fact that there are few radionuclides that contribute to the peak dose within the regulatory compliance period; among these, Np-237 (half-life of 2.1×10^6 years) is the most important based on preliminary studies. Np-237 is the radionuclide with the best

[14] The DC Circuit Court of Appeals [NEI v. EPA] recently ordered the USEPA to revise the regulatory standard to incorporate a longer compliance period as recommended by the NAS in *Technical Bases for Yucca Mountain Standards* [NAS, 1995].

potential to produce the regulatory dose limit of 15 mrem/yr within 10,000 years. USNRC studies [McCartin, 2003] have shown that the other radionuclides that are commonly highlighted as large contributors to dose are very unlikely to be able to produce the required dose (>15 mrem/yr.) While Tc-99 (half-life ~10^5 years) commonly makes up the lion's share of the pre-10,000 year doses, these are doses that are about 3-5 orders of magnitude *below* the regulatory limit. USNRC studies estimate that 7,000 WPs (more than 2/3 of the total) would have to be breached early to release the Tc-99 activity in curies (Ci) necessary to exceed the regulatory dose limit. The number of WPs that, if breached, would release the required Ci of Np-237, on the other hand, is on the order of a few tens or a hundred. Am-241 and Pu-240 make up a large share of the initial radionuclide inventory (spent nuclear fuel) at the time of closure and in theory could produce the required regulatory dose, but their high retardation in the geosphere and relatively short half-lives (~400 years) render them less important actors. Studies estimate that it would take hundreds of thousands of years for Am-241 and Pu-240 to travel the 18 km to the dose receptors [McCartin, 2003]. This leaves Np-237 as the primary actor. Since Am-241 decays to Np-237 and hence acts as an additional source of Np-237, it must also be included in the focused PA calculations, as well as Cm-245 which is a parent of Am-241 (see figure 3.3 for an illustration of the Cm-245/Am-241/Np-237 decay chain).

We further focused the calculations by looking at only drinking water dose contributions in the base case (as mentioned above). This reduces the number of uncertain parameters, *n*, from 330 to ~200. Parameters eliminated are those that (1) describe behavior of the 29 other radionuclides, (2) relate to plant and soil radionuclide uptake properties relevant only for farming scenarios, and (3) describe disruptive volcano scenarios.

The USNRC has performed sensitivity analyses on the parameters in the TPA 4.1, and has ranked the parameters according to numerous methods including stepwise regression analysis, Kolmorogov-Smirnov test, the Morris method, and differential analysis (see [Mohanty et al., 2002] for an extensive description of all the methods and findings.) We use these findings to create the following preliminary list of potentially important repository attributes as represented in the TPA parameters:

1. Infiltration rate, AAMAI@s (hereafter called Infil), is the average rain infiltration into the mountain at the start of the simulation.
2. Condensate (from infiltrated rain water) moving to the repository, FOCTR, is the fraction of condensate in the mountain that is moving toward the repository.
3. The Waste Package Flow Multiplication Factors, WPFlowMF (hereafter called WPFF), represents flow focusing or diversion effects and is a key measure of how much water can reach the waste packages.
4. The subarea wet percent, SubAreaWet% (hereafter called SAW%), is the percentage of the repository that has water above it. In other words, the available water may not cover the entire repository (in fact, is unlikely to do so); this parameter is the percentage of the repository that ends up with the available water.
5. The drip shield failure time, DSFailTi (hereafter called DSFT), is the time at which the drip shield fails, i.e., develops at least one hole that allows water to contact the waste package below.
6. The initial waste package defect rate, WPDef% (hereafter called IWPD), is the percentage of waste packages that are initially defective (because of weld manufacturing defects), and hence this percentage of waste packages have the only inventory that is available to become the source term before general corrosion begins to fail waste packages tens of thousands of years into the future.
7. Spent fuel wet fraction in subarea 1, SF1Wt%, is the percentage of spent fuel that is wet (once water has entered the WP) in subarea 1. In the USNRC TPA, the repository is divided into 10 subareas, according to geologic properties that can be considered uniform within these spatial areas.

8. A key term in the spent fuel dissolution model, PSFDM1 (hereafter called SFD), is the pre-exponential spent fuel dissolution term in fuel dissolution model 1 (which is the default model in the PA).
9. The solubility of Np-237, SolblNp (hereafter called SOL), is an important parameter because in the default spent fuel dissolution model, the solubility limits how much Np-237 can enter water contacting the spent-fuel waste form.
10. The K_d in a key UZ unit, MKDCHvNp, is the sorption coefficient for Np in the Callico Hills nonwelded vitric unit, an important geologic unit in the UZ.
11. The retardation factor in a key SZ unit, ARDSAVNp, is the retardation factor for Np in alluvium, an important geologic stratum in the SZ.
12. The well pumping rate, WPRRG@20, is the well pumping rate for the hypothetical farming community living 20 km away from the repository.

Of these parameters, we dropped the last one from further consideration, because, in the current regulations, the well pumping rate is prescribed and therefore no longer uncertain for our purposes. We tried to confirm the importance of the remaining parameters by employing generalized sensitivity analysis (GSA)[15] (described in [Hornberger and Spear, 1981]) running the TPA base case with a LHS size of 500 realizations; of these, 21 failed[16]. While the results of GSA should be similar to those of the K-S test, our application was somewhat different since we used repository SID as the partitioning criterion, i.e., binning SID realizations together, and success realizations together, and we were looking for findings other than whether the values in the two bins came from different distributions. Specifically, the GSA can indicate (1) how important the attribute is, based on the largest vertical distance between the cumulative distribution functions for values in the two bins [Hornberger and Spear, 1981], AND (2) whether there are threshold effects, which is of particular importance for our goals.

[15] We used this as an independent check, since the USNRC had not used this as one of their methods (they used several others) to compile the list above.
[16] We ran the TPA base case multiple times with LHS size 500, with consistent results.

We found that no one parameter *alone* can make the repository produce SIDs (an expected result for a multi-barrier system); we did find, however, that there are some parameters that seem to be able to prevent repository SID on their own. The SFD term is the most dramatic example of this. Figure 3.4 shows the partitioned CDFs for this parameter; the solid grey line shows the CDF for the SFD values in the 21 SID-producing realizations, and the dashed black line shows the CDF for the 479 non-SID realizations. Based on these realizations, where the lowest value of SFD resulting in SID is $\sim 1.5 \times 10^4$, it seems that SIDs would be very unlikely if the true value of the SFD is less than 10^4, which corresponds to roughly the first third of its distribution. Figure 3.5 shows the partitioned CDFs for another parameter, WPFF, demonstrating both a potential threshold effect (no SIDs observed for WPFlowMF<~10), as well as general importance based on the distance between the two CDFs. We confirmed that most of the remaining parameters were indeed important based on the GSA results. As a control, we checked several parameters that should not show up as important; one example is the AA_1_1 parameter which is the key WP general corrosion parameter and one that is very important for repository performance at larger time scales (40,000-100,000 years). As expected, GSA showed no importance for AA_1_1 for the 10,000 year time frame, as shown in Figure 3.6. The two CDFs are very close to each other, correctly indicating that this parameter is not important for doses within the first 10,000 years after closure.

It turns out that for the 10,000-yr 10-km dose, the general importance of the key UZ sorption coefficient (MKDCHvNp) and key SZ retardation factor (ARDSAVNp) parameters was swamped by the other attributes. At least for the SZ retardation factor, this makes sense; since it is SZ property and we have reduced the SZ between the receptor and the repository, naturally the importance of this attribute is diminished. Despite these results, we kept them on as potentially important attributes for the next step. As for the parameter describing the percent of spent fuel that is wet in subarea 1 (SF1Wt%), we used a different parameter that makes more sense for the purpose of our analysis. Subarea 1 has the largest number of WPs, and therefore the SF1Wt%

shows up in many SAs, whereas the percentage of spent fuel wet in other subareas does not. But what is really most important, is the *total percent* of spent fuel that is wet across the entire repository. This is not captured by SF1Wt% alone. So we used another lumped parameter, the average of the 10 subarea spent fuel wet percentages, and called this the Spent Fuel Wet Percent (SFWt%).

Starting with this list of potential explanations for repository SID/success, we will now find SID scenarios, step 2 of the analysis.

2a. Find SID scenarios

To reduce the dependence on particular LHS samples, we ran the TPA again with a LHS size of 200, calculating doses from the Cm-245/Am-241/Np-237 radionuclide chain only. Of these 200 realizations, 9 (4.5%) crossed the goal of 15 mrem/yr. Figure 3.7 shows the 'spaghetti' curves for the 120 realizations that resulted in non-zero doses within the 10,000-yr time frame; the 9 realizations that 'failed' are shown in black. Figure 3.8 shows summary statistical measures for all the realizations. Just as each risk curve in Figure 2.2 was predicated on one particular value assumed for the uncertain parameter, λ, each curve in Figure 3.7 is predicated on one set of assumed values for all uncertain parameters in the TPA code. Each of the curves in Figure 3.7 is not, however, a risk curve as defined above. Since the regulatory performance measures for the WIPP and YMR are different, the PA results show different kinds of performance. To construct risk curves similar to those shown in Figure 2, we could take a vertical slice of all possible doses at a given future time on the x-axis in Figure 3.7, and construct a dose CCDF that would represent *all* the uncertainties encompassed by the parameter distributions, *not* just the aleatory uncertainty as defined for the WIPP and as shown in Figure 2. So whereas the family of risk curves for WIPP displayed the aleatory (scenario) and epistemic (parameter and model uncertainty) uncertainties separately, these uncertainties are collapsed together to some degree into the curves that are constructed in YMR PAs. The mean curve (and percentile curves) in Figure 3.8 is not the outcome of any particular set of parameter values; rather, the mean is constructed by calculating for each time on the x-axis the average of all doses from the multiple realizations, and then connecting these points.

For the 9 SID realizations shown in Figure 3.7, we checked the sampled values for the key attributes identified in step 1, in order to find an explanation for the SIDs. Table 3.1 shows the percentiles sampled for some of these key parameters (the ones with the most initial explanatory value,) for the realizations that resulted in the 4 highest peak dose. For example, for the realization where the peak dose was 101 mrem/yr, the sampled value of the Waste Package Flow Multiplication Factor (WPFF) parameter corresponded to the 99th percentile of its distribution, and the sampled value of the initial WP defect rate (IWPD) corresponded to the 98th percentile of its parameter distribution, and so on. Recall that the first three parameters are a measure of how much water can get to the waste packages (WPs) in the repository from infiltrating rainfall and flow focusing effects. The fourth parameter is the initial defect rate in the WPs, i.e., weld failures at the start of the simulation. The fifth parameter is Np-237 solubility, which is thought to be the controlling factor for the release of Np-237 from spent fuel (the main waste form.) And the sixth is a key parameter in the spent fuel dissolution model. The percentiles are listed in the direction of values that are worse for performance, e.g., performance is worse with increasing values of initial WP defect rate. All the percentiles are shown, but only those that fall in the top fifth of their distributions are bolded, since they are more likely to help explain the high-dose results.

On inspection, it appears that the WP flow factor (WPFF), Initial WP defect rate (IWPD), and Np solubility (SOL) have a significant potential to create large doses if high percentiles of these parameters are sampled together. At the same time, these factors alone do not determine whether there will be a high dose because there were plenty of realizations where high values of these parameters were sampled without resulting in a high dose. In order to build a class of scenarios based on this, we can perform conditional sensitivity analyses on the remaining attributes, given high percentiles sampled for these three parameters, to find repository features that may save us from the challenge posed by high WPFF, IWPD, and SOL. The purpose is to build an understanding of what poses a challenge to the repository system, and what repository attributes can mitigate these challenges, and try to quantify the probabilities of different possible scenarios.

2b. Find savior attributes

We wish to find what set of attributes can save us from the challenge of high IWPD, WPFF, and SOL. As a basis for our conditional sensitivity analyses, we ran the TPA again, with a LHS size 50 starting with the condition that the WPFF, IWPD, and SOL values lie in the top 5% of their pdfs (i.e., F(x)>0.95), and that the drip shield fails before 10,000 years (the first 82% of the DSFailTi distribution), since the dose is zero in the base case if the DS is intact for the first 10,000 years. Table 3.2 shows a summary of the peak dose statistical measures.

We used GSA for single parameters, both step-wise and on the entire set of realizations. For the step-wise case, we first found which parameter could explain best the successful realizations out of the whole set, and removed the realizations 'saved' by this parameter; then found which parameter could best explain the successes in the remaining set of realizations, and removed those realizations explained by it; and so on, until single parameters could no longer explain the success/SID divide in the remaining realizations. Using GSA for single parameters yielded the following insights: (1) the drip shield, which is a barrier (like an umbrella) to water reaching the waste package, obviously must fail before the 10,000-year compliance period. The dose is zero for the 18% of realizations where the drip shield failure time (DSFT) is after 10,000 years. And, with a high degree of confidence, we find that the peak dose will not exceed 15 mrem if: (2) SFD, a key term in the spent fuel dissolution model lies within the first 26% interval of its distribution; (3) SubAreaWet% (SAW%) is less than 10%; and (4) SFWt%<10%. But this still leaves a lot unexplained. So we looked at how sets of parameters might explain the results further.

Scatter plots of SIDs and successes for two parameters at a time can help identify threshold effects, similar to those identified by GSA for single parameters. It makes sense that some parameters working in concert will become more important than either one alone – for example, while the rain infiltration parameter (AAMAI@s, or Infil) alone did not yield any threshold effects, the infiltration considered along with the percent of the subarea that is wet (SAW%) might. Using scatter plots two parameters at a time, we found that the rain infiltration parameter combined with either the subarea wet *% or* condensate moving towards the repository (FOCTR) parameters, *did* exhibit threshold effects. The scatter plot of AAMAI@s (Infil) and SAW% is shown in Figure 3.9. The absence of SIDs in the lower left corner of the sample space could indicate a threshold effect for combinations of low values for these two parameters. This adds the insight that, with a high degree of confidence, we find that the peak dose will not exceed 15 mrem/yr if: (5) Infil. < 8.5 mm/yr *and* SAW%<45%; or (6) Infil.<8.5 mm/yr *and* FOCTR<25%. Two of the 50 realizations could not be explained by these savior attributes. Most likely we would have to seek out higher order explanations for these, e.g., numerous parameters working in concert to prevent repository SIDs (which of course is what the repository is designed to do.)

In order to confirm the above hypotheses about savior attributes, we compared them with GSA findings from the 500-realization base cases, and we tested some of them using smaller LHS sizes (~20); e.g., we forced the key spent fuel dissolution term (SFD) into the bottom 30% and forced the other parameters into the ranges of their respective distributions where SIDs were possible, and checked whether the postulated savior attribute did still prevent repository SIDs. While this is not enough to say with certainty that our hypotheses are indeed true for all cases (the entire response surface,) it does increase our confidence in the results.

Of course this is not the only class of scenarios, there are many other ways for the repository to produce SID; this set is just an example. Using these results, we can move to step 3.

3. Explain reasons for SIDs and display results in SPARC tree

Based on the above analyses, we can construct the tree shown in Figure 3.10, for the scenario that begins with the challenge that IWPD, WPFF, and SOL are all in the top 5% intervals of their respective pdf's. The SPARC tree displays the results that, even if the WPFF, IWPD, and SOL were all in their worst 5% intervals of their respective pdfs (the initial postulated challenge) the repository fails *only if* DSFT>10^4 years *and* F(SFD)>0.26 *and* F(SAW%)>0.1 *and* F(SFWt%)>0.1 *and* the savior conditions for Infil with SAW% *or* FOCTR are not true, as shown on successive branches. The probability for each branch that can lead to SID is shown below the branch.

4. Assess scenario probabilities, and probe supporting evidence

Based on the existing distributions for the parameters in the TPA, the preliminary probability estimates for SID from this class of scenarios that starts with high WPFF, IWPD, and SOL is on the order of[17] $(0.05)^3(0.36) \cong 4.5\text{x}10^{-5}$. One may ask why we should bother with these analyses, since our preliminary assessment shows a low probability of exceeding the decision threshold. One answer is that we may be wrong about the low probabilities we assign to some of the challenges, because of incompleteness. For example, what if we are wrong about the structural assumptions, **M**, in our MOWs? Identifying which repository attributes are important through the SPARC analyses, we can focus on resolving or exploring alternate plausible M_i's for

[17] Assuming independence among the parameters, the probability that WPFF, IWPD, and SOL are each in the top 5% intervals of their respective distributions is $(0.05)^3$; and based on the SPARC tree, the probability of missing *all* the savior attributes is ~0.36. The total probability for this scenario, assuming independence, is $(0.05)^3$ x (0.36), or ~$4.5\text{x}10^{-5}$.

the most risk-significant attributes. Making investments to strengthen the repository system, we should target risk-significant areas, including areas of large important uncertainties. For one specific example, consider that the SFD distribution currently spans three orders of magnitude, and values in the lower 26% of the distribution range have high worth as a repository savior attribute. If experiments could help narrow this distribution, particularly if the distribution were found to be skewed toward lower values, confidence in the repository could increase tremendously. As another example, the SAW% has a large potential as a savior attribute, either by itself or in concert with the water infiltration rate. While there is not much one can do about the infiltration rate (which is tied to how much rain falls on the mountain in the future), the SAW% can be considered a proxy for the capillary barrier that the USDOE assumes will prevent water from percolating directly into the repository (it is assumed that the water will rather drip along the walls of the repository and not onto the drip shield for a very long time). If research can help confirm that the capillary barrier will indeed be effective in 80-85% of the drift areas, our confidence in the repository system would be increased considerably.

3.2.2 YMR Case Study – Corrosion of Waste Package

Recently, the US Nuclear Waste Technical Review Board (NWTRB) raised concerns about the localized corrosion of waste packages (WPs) during the initial disposal phase in the USDOE's current YMR design for the high-temperature operating mode (HTOM). "Based on its review of data gathered by the DOE and the Center for Nuclear Waste Regulatory Analyses, the Board believes that all the conditions necessary to initiate localized corrosion of the waste packages will likely be present during the thermal pulse" [NWTRB, 2003a]. The NWTRB admitted in its letter that it is not sure of the implications of their findings for system-level performance; rather, they expect the DOE to address them.

In this section, we illustrate how the SPARC analyses could be used for proper disposition of this technical concern. The possibility of a new corrosion mechanism may or may not be of concern, depending on its effects on projected risk and uncertainty. First, we describe the specific phenomena of concern, and match these to existing elements in the USNRC's PA capable of approximating the effects of these phenomena. Then we can draw conclusions about the corrosion concerns.

The NWTRB claimed that localized corrosion can be a concern if the following conditions exist simultaneously: (1) waste package surface temperatures are above 140°C; (2) concentrated brines are present, such as those formed in the deliquescence of calcium and magnesium chloride; and (3) crevices exist on the WPs. The USDOE's 2001 PA assumes that more than 1 early WP failure is very unlikely. The NWTRB reviewed the USDOE's technical evidence for this assumption and other data available in the open literature, and disagreed; the NWTRB concluded that localized corrosion due to deliquescence is likely in the HTOM design because the above conditions likely will exist simultaneously [NWTRB, 2003a].

We can use the early weld failure mode in the TPA 4.1j code as a proxy for small holes created by localized corrosion and test sensitivity of repository performance to changes in the parameter θ_i = IWPD, and hence the concerns raised by the NWTRB. First, we can test how many WPs would have to fail to exceed the regulatory criteria (moved to the 10-km location). We find that the PA base case average dose can get to 15 mrem if we postulate that early WP failures lie between 0.01% and 5.5%; whereas the current IWPD distribution lies between 0.01% and 1%.

But the NWTRB's concerns also imply that the number of early WP failures would be connected to the amount of water reaching WPs, since the water and humidity contribute to the localized corrosion. This would call into question one of the original structural assumptions, M_i, in our MOW, namely that the % of early WP failures and amount of water contacting the WP are independent. The synergistic effect identified by the NWTRB could increase the probability of early WP failure. In other words, whereas in the original SPARC tree in Figure 3.10 the IWPD and WPFF were independent of one another, now they no longer are. We had originally calculated the probability contribution of both the IWPD *and* the WPFF being in the highest 5% intervals of their respective distributions, under an independence assumption, as 0.05*0.05 = 2.5×10^{-3}. But now, the synergistic effect implies P(High IWPD | High WPFF) > P(High IWPD) * P(High WPFF); in other words, the probability contribution from high values of these two parameters would be greater than 2.5×10^{-3} (see Figure 3.11). So the total probability for this class of scenarios would increase if early localized corrosion is indeed possible. Without further studies (some of which are under way at national labs in research sponsored by the USDOE), we can not quantify the effect but we can identify it as potentially important.

3.3 Discussion

Perhaps because of the regulatory criteria, existing PAs in the US are focused on producing reliable projections of the *mean value* of future consequences, along with a display of all the multiple realizations (like those in Figure 3.7) used to calculate that mean. But it would be useful to also have specific information on *how* HLW repository systems may produce SIDs. Similarly, existing sensitivity analyses indicate which parameters and model uncertainties are important to system-level performance, but they do not identify specifically what parameter-assumption ranges may lead to repository SIDs, and what parameter-assumption ranges prevent repository SID. In addition, we know there is incompleteness in our models and that all structural model uncertainties are not propagated to system-level performance in the overall PAs. Unfortunately, we do not have the resources to study all of these uncertainties.

More explicit risk information is important for various reasons, including: (1) building confidence in the repository system, particularly as part of defense-in-depth activities in a safety case, (2) allocation of resources for future research efforts on those uncertainties that are most significant to risk, and (3) informing stakeholder deliberation about what is important from a repository risk perspective. In this chapter, we proposed the SPARC tree method as a supplementary analysis to PAs, extracting and displaying risk information from *existing* PAs for HLW repository systems. We illustrated the SPARC tree method through an example using the Yucca Mountain Repository system. SPARC trees can display explicitly *how* the repository may produce SIDs, by identifying SID scenarios and repository attributes that act as saviors, even under extremely challenging conditions. These attributes can be quantified in existing parameter ranges, as demonstrated. The results from the SPARC trees should be particularly useful as risk information for decisions on future research efforts; for example, the rate of spent fuel dissolution was found to be a key parameter in the YMR PA with large uncertainty. Better quantification of this parameter, not necessarily in an absolute sense but merely to determine how likely it is that the true value lies in the first quarter of the existing distribution (since this is the strategic partition that is important,) through better use of existing information and through conceivable laboratory experiments, could increase our confidence tremendously since it has a large potential to act as a savior attribute for even extreme conditions. The example case study also illustrates the usefulness of SPARC trees for informing stakeholder deliberation. The SPARC trees help focus on why specifically the concerns raised could be important from a risk perspective. SPARC trees could be very useful as a supplement to PAs and as a basis for risk-informed decision-making.

Figure 3.1. Schematic diagram of the proposed Yucca Mountain Repository system (not to scale)

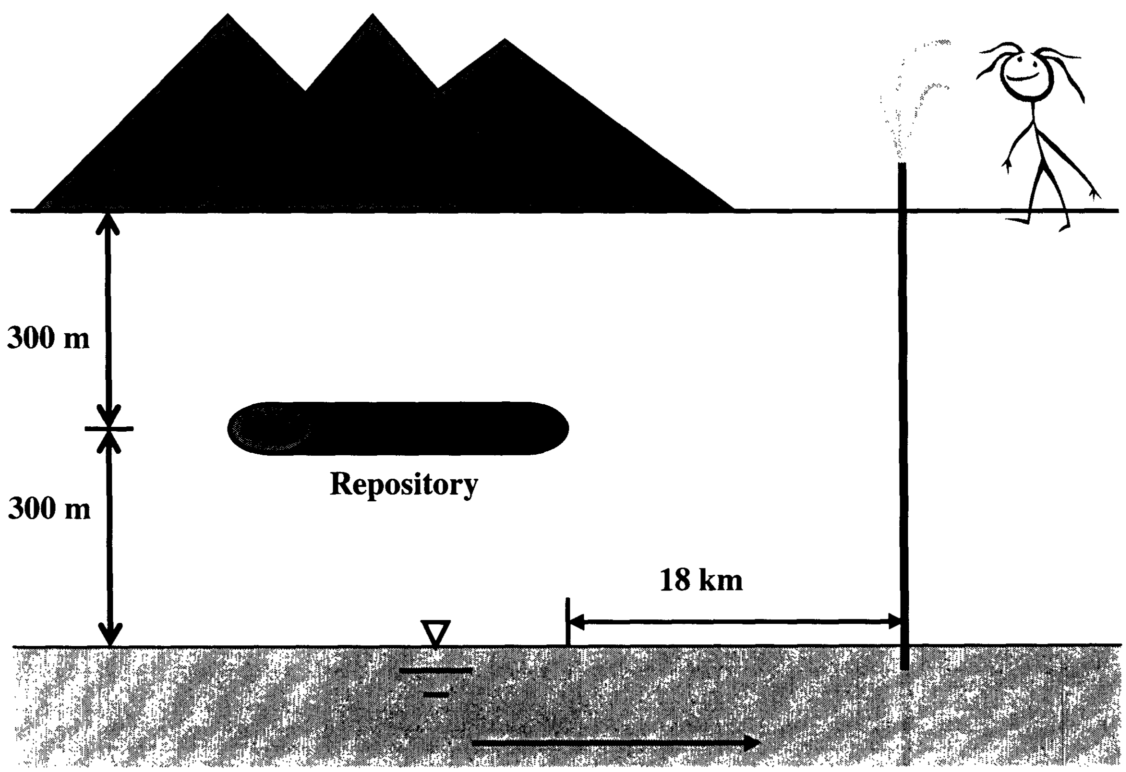


Figure 3.2 Cross-Section of one drift/tunnel in YMR (not to scale).

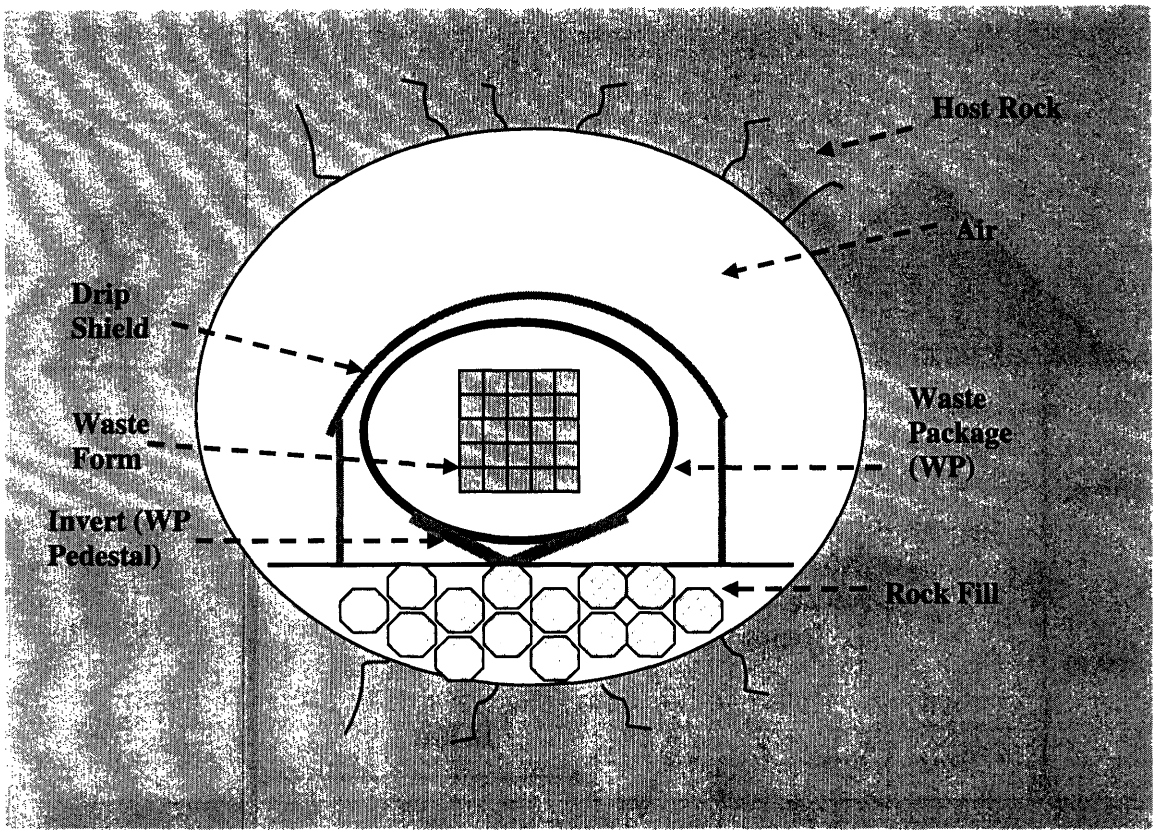


Figure 3.3. Illustration of Cm-245/Am-241/Np-237 decay chain (based on [Radiochemistry Society, 2004]). Half-lives for each isotope are shown in parentheses.

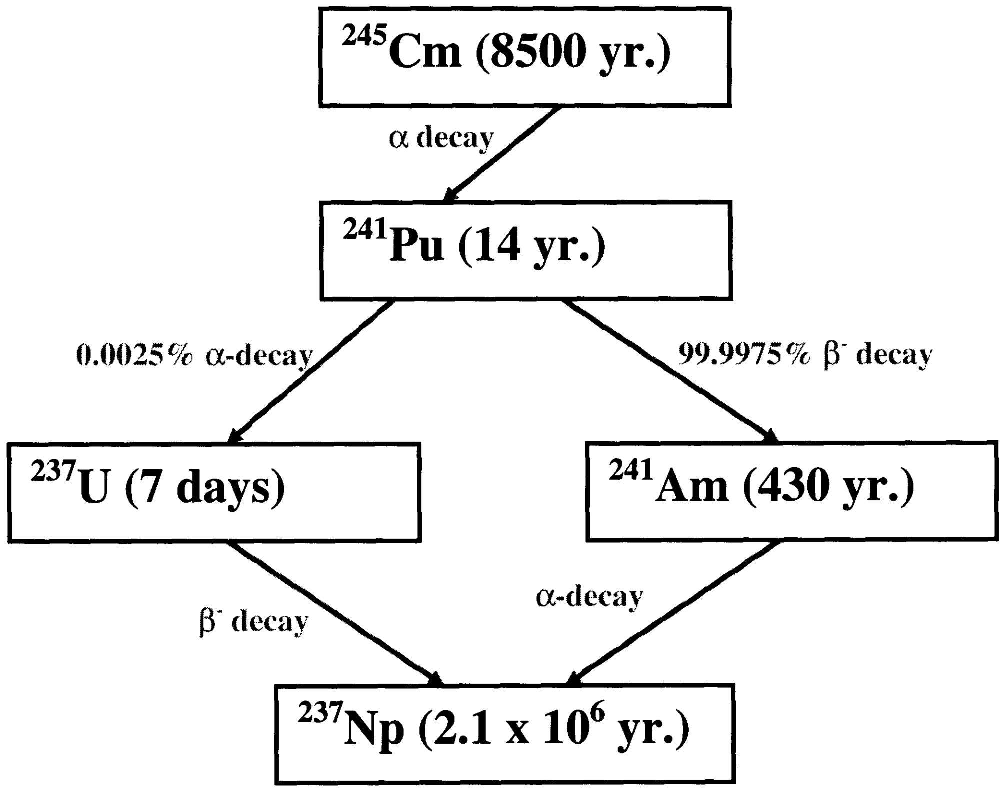


Figure 3.4 Generalized Sensitivity Analysis (GSA) based on Cumulative Distribution Function (CDF) partitioning for the Pre-exponential term in the Spent Fuel Dissolution Model 1. CDF for SIDs plotted in the grey solid line; CDF for success values is plotted in the dashed black line.

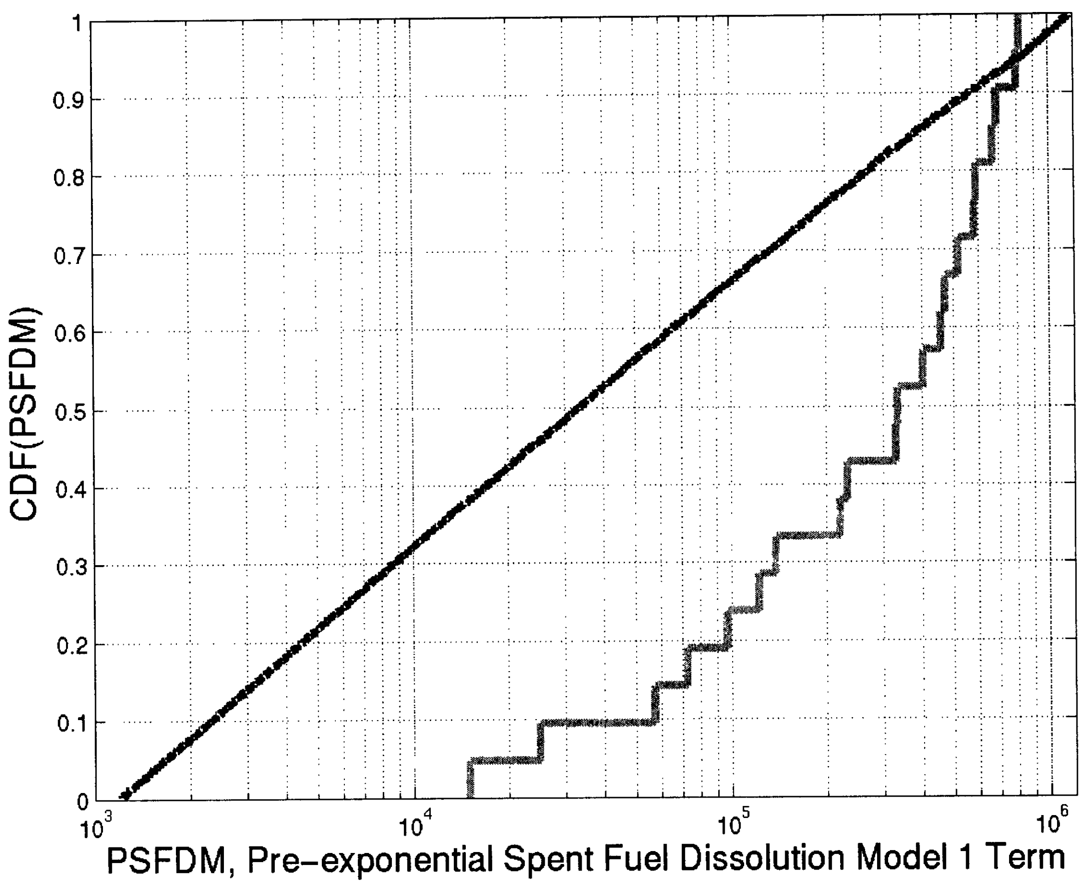


Figure 3.5 GSA for the Waste Package Flow Multiplication Factor parameter, WPFlowMF. SID CDF in solid grey line; success CDF in dashed black line.

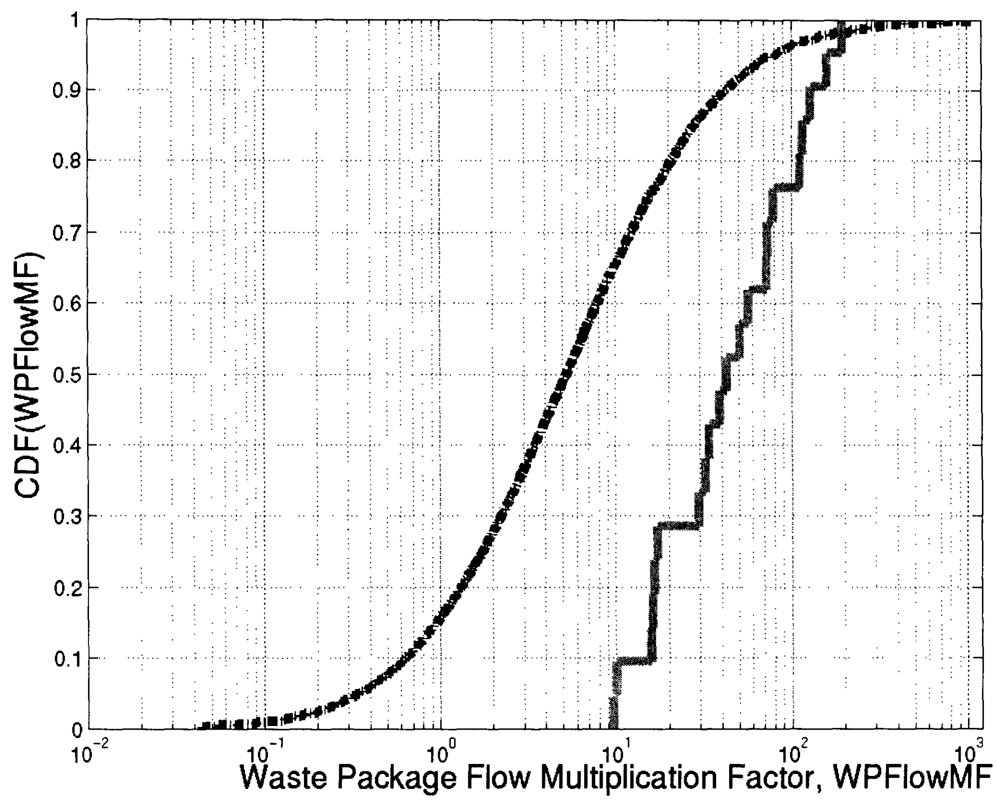


Figure 3.6. GSA for key waste package corrosion parameter, AA_1_1. SID CDF in solid grey line; success CDF in dashed black line.

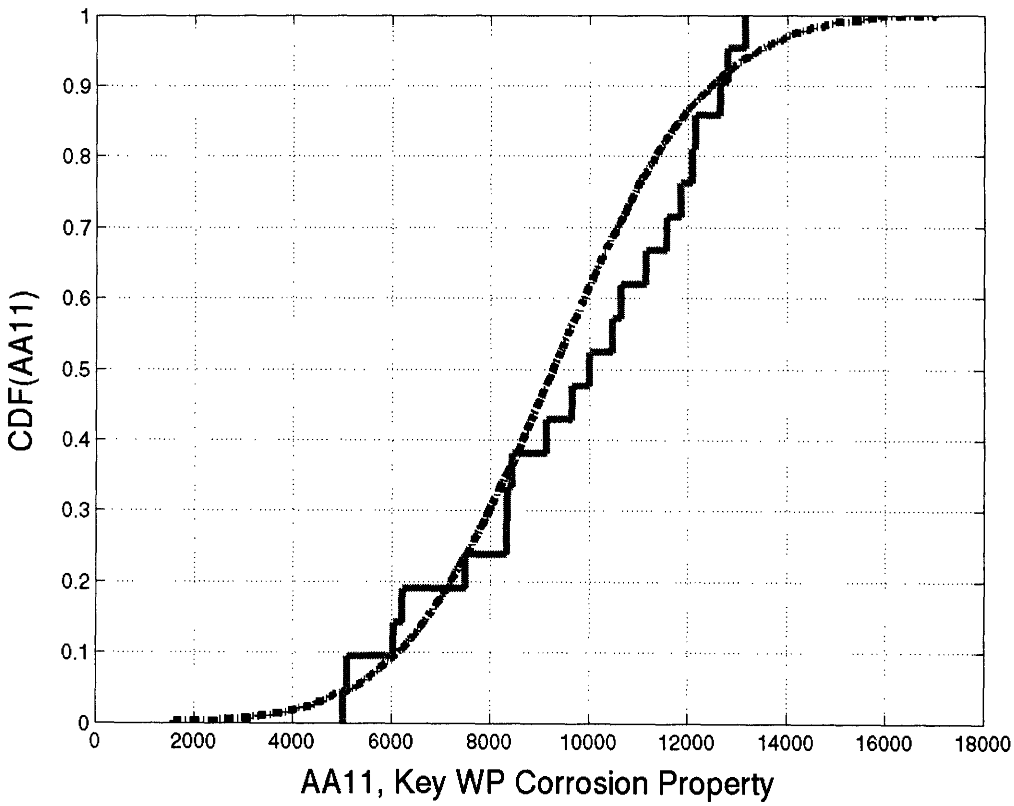


Figure 3.7. Np-237 dose (rem/yr) to 10 km-receptor using TPA 4.1j Code, 200-realization base case. SID realizations in black, 'successes' in grey.

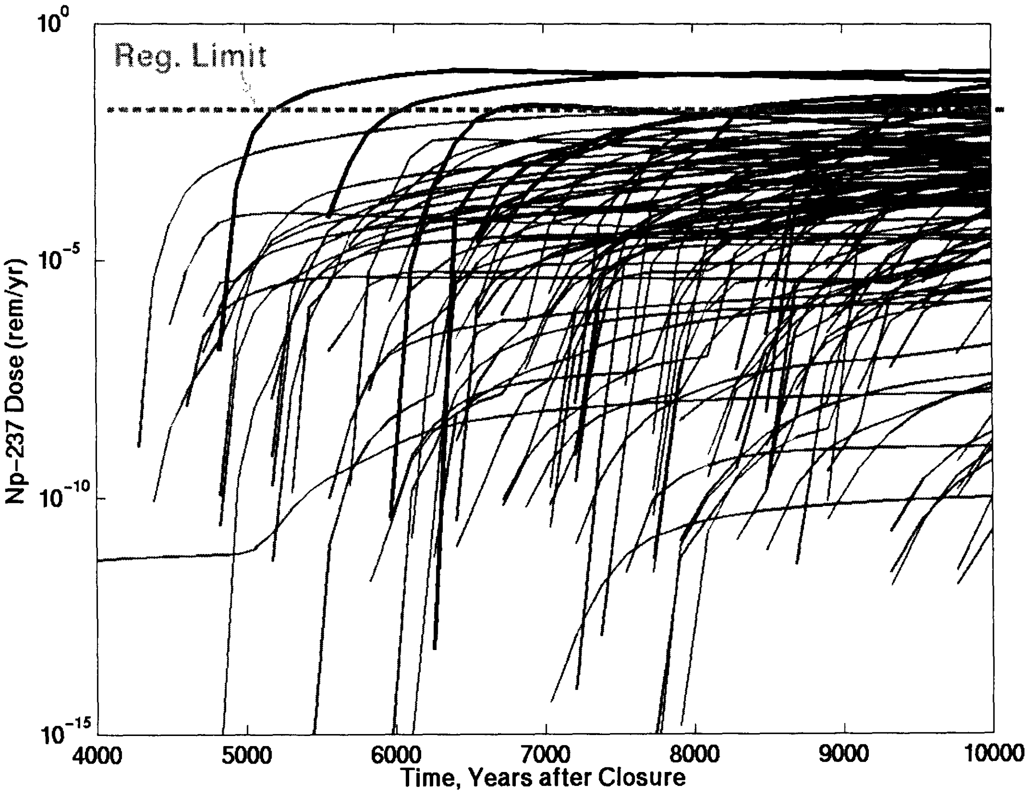


Figure 3.8 Np-237 dose (rem/yr) summary measures for 200-realization base case in Fig. 3.7. These summary curves are *not* the result of any one set of chosen parameter values (one realization). The summary curves are constructed in the following way: (1) for each point in time (x-axis), the point values for dose from all the realizations are averaged to get the mean value for that point in time; the median point is found where half of the doses realized at that time lie below and half above; the *n*th percentile point is where n% of the realizations lie below and (1-n)% lie above; (2) then all the mean points are connected left-to-right to form the mean curve, the median points are connected to form the median curve, and so on.

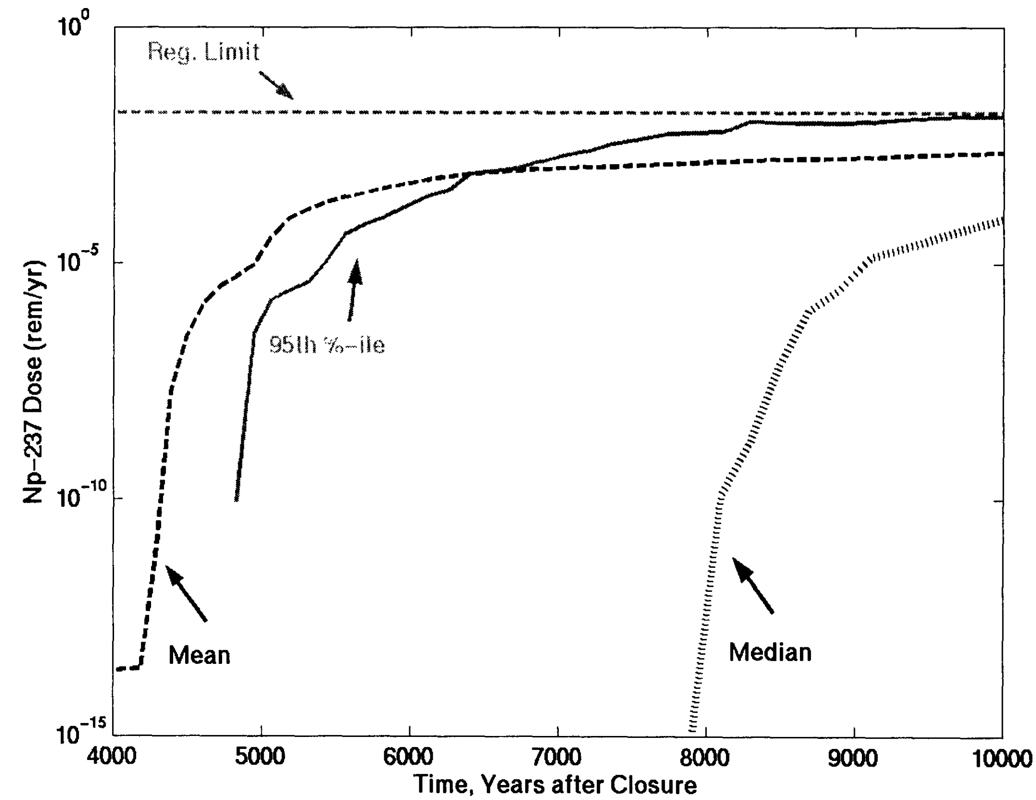


Figure 3.9 SIDs (▲) vs. Successes (●) in space of sampled values from infiltration rate (AAMAI@s) and Sub-Area Wet % parameter distributions.

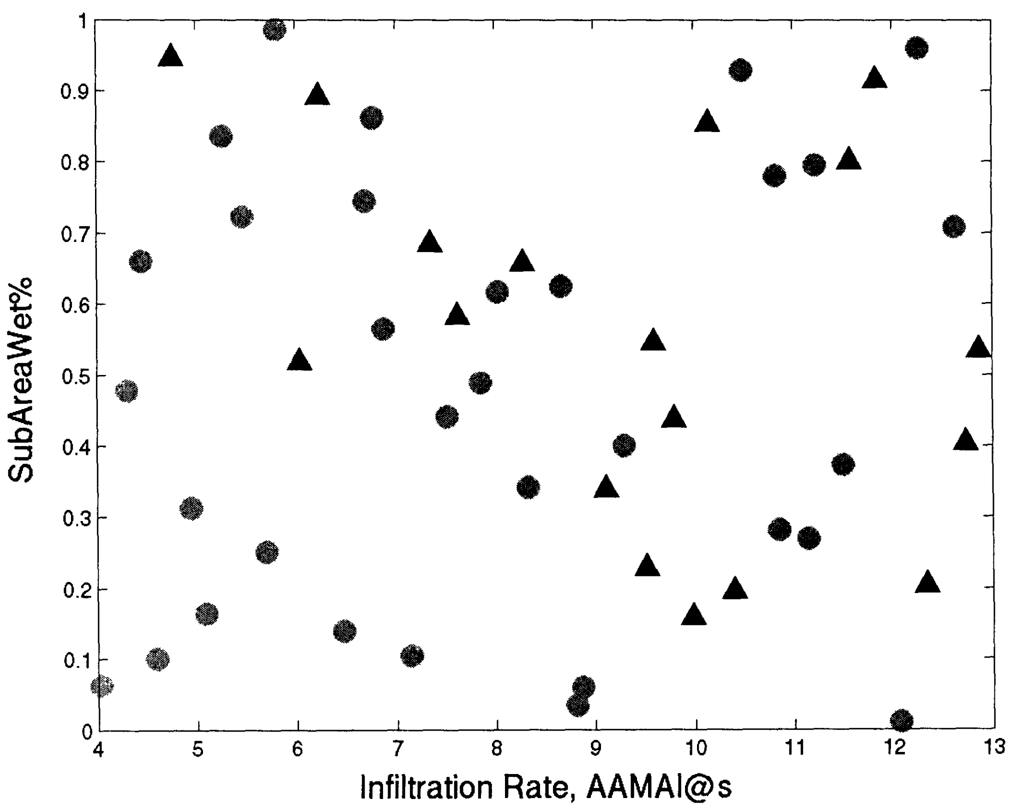


Figure 3.10 SPARC tree for class of scenarios starting with WPFF, IWPD, and SOL in the worst 5% intervals of their respective parameter distributions. The probability for strategic partitions for each repository attribute (represented by the appropriate model parameter) is shown below the branch.

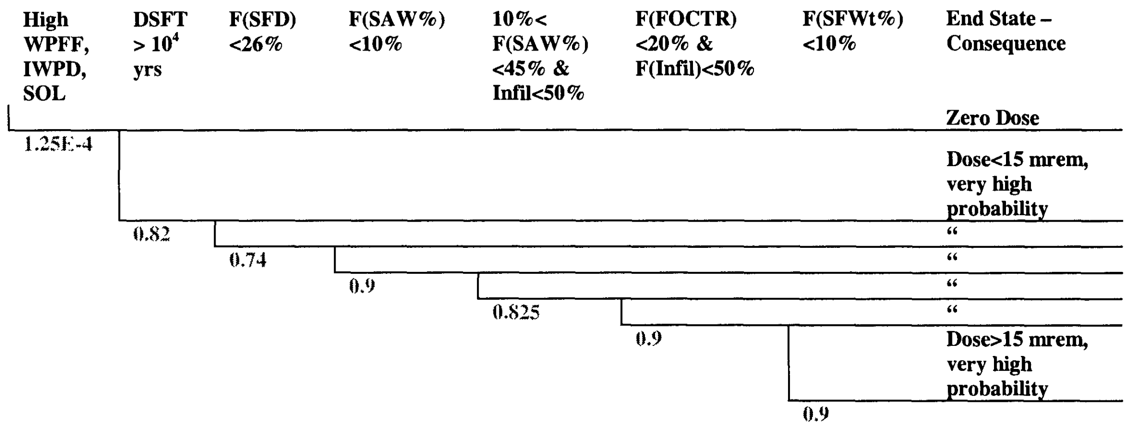


Figure 3.11 SPARC tree for class of scenarios in Figure 3.10, with implication of NWTRB's early corrosion concerns.

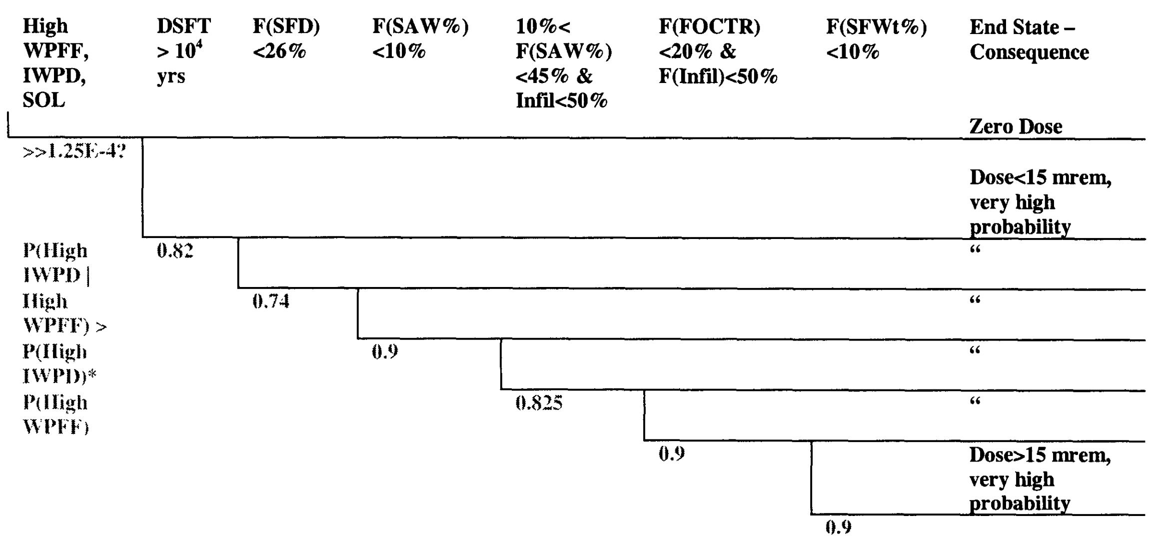


Table 3.1 Distribution percentiles for parameter values sampled for six key uncertain parameters in four worst realizations in 200-realization base case for Np-237 Dose to 10-km receptor.

Np-237 Dose (mrem/yr)	Infiltration @start (Infil)	WP Flow Factor (WPFF)	Sub-Area Wet% (SAW%)	Initial WP Defects (IWPD)	Np-237 Solubility (SOL)	SF Dissolution Term (SFD)
101	19%	**99%**	36%	**98%**	**97%**	**90%**
97	8%	**97%**	43%	**80%**	**96%**	**94%**
48	**97%**	**95%**	**99%**	69%	56%	38%
30	35%	**94%**	**94%**	**96%**	**89%**	45%

Table 3.2 Peak dose statistics for 50-realizations of scenario of "high" initial waste package defect rate (IWPD), waste package flow multiplication factor (WPFF), and Np-solubility (SOL)

Average peak dose	37 mrem/yr
Median peak dose	6 mrem/yr
5th percentile peak dose	0 mrem/yr
95th percentile peak dose	141 mrem/yr
Peak dose in worst realization	261 mrem/yr
Percent of realizations that were SIDs	36%

Chapter 4. Risk Information for Productive Public Discourse about HLW Repositories

4.1 Introduction

The management of spent fuel and high-level nuclear waste (HLW) generated in the production of nuclear power has been a contentious issue around the world, wherever nuclear power is in use. Many countries, including the US, are in the process of developing long-term management programs that include underground repositories for HLW disposal or long-term storage. There are two main (inter-related) sources of disagreements about HLW repositories: (1) differing societal values and priorities, and (2) differing scientific judgments about how the HLW repositories are likely to perform. The first category includes concerns about risk-risk and risk-benefit-cost tradeoffs, such as what kind of adverse health effects are tolerable for the benefits reaped from energy production; and ethical concerns about the distribution of risks, costs, and benefits across individuals, sub-populations, and generations of society (for example, see [Shrader-Frechette, 1993]). The second category includes all of the disagreements inherent in a complex-system modeling exercise, such as that required for HLW repository PAs. PAs of complex engineered-geologic systems for 10^4-10^5 years naturally entail extensive uncertainties that are a major source of disagreements among scientific experts and stakeholders.

In the previous chapter, we presented the SPARC method for extracting information from existing PAs and displaying it in SPARC trees to show how a repository may 'fail' or be 'saved' by collections of repository attributes. As noted, the SPARC analyses can help build confidence in the repository system, focus future research efforts, and inform stakeholder deliberation by concentrating resources on specific parameter-assumption ranges that are important. In this chapter, we focus on determining what risk information is of interest to stakeholders and demonstrate how this risk information can be collected with existing PAs and using SPARC analyses, with the objective of improving the public dialog on repository risk. The ultimate goal is to build consensus on what decisions are acceptable in HLW repository programs. While fundamental differences in values and priorities across stakeholders are unlikely to change, open acknowledgment and discussion of stakeholder concerns may help foster more effective and efficient solutions to societal risk problems[18] by identifying areas of consensus and disagreement, and building a more productive path to resolving the disagreements. For HLW repositories in particular, focusing on the situation in the US, there are three good reasons to seek a risk discourse that is more productive in resolving disagreements. (1) There are numerous *conflicting and ambiguous technical claims* about the projected future performance of repositories, contributing to public confusion. (2) Many stakeholders have concerns about the current *decision-making processes* in place for the Yucca Mountain Repository (YMR), and feel disenfranchised. (3) Many stakeholders have special concerns about radioactive waste because of the *nature of the risk and perceptions of radioactivity.*

4.1.1 Conflicting or Ambiguous Technical Claims

In the public literature in the US there are numerous conflicting claims about how well the proposed US HLW repository, the YMR, will perform, and the main factors that should be considered when projecting performance. Two examples of claims in the literature are: (1) The repository developer, the US Department of Energy (USDOE), whose current repository design relies heavily on corrosion-resistant metal canisters to contain the HLW, presents the fact that a

[18] For examples, see Finnish and Swedish HLW repository site selection successes described in [NEA, 2003]; the six cases of risk analysis and characterization including protection of the Florida everglades, siting and approval of a waste incinerator in Liverpool, OH, and negotiated regulatory rule-making for disinfectant by-products described in [NRC, 1996]; and the case of International (US-Canada) Joint Commission on Great Lakes Water Quality described in [O'Brien, 2000].

similar corrosion-resistant metal was found to survive marine environments for almost 60 years, retaining a mirror-like finish and suffering virtually no corrosion [USDOE, 2004; Bechtel SAIC, 2003], with the implication that this is good evidence that the chosen metal will indeed do well in protecting the HLW in an underground repository. (2) The Governor of the host state, the State of Nevada, claims that volcanic activity in the vicinity of Yucca Mountain may be a serious challenge to the repository system in the future [Guinn, 2002]; the Governor states that there have been three volcanic eruptions within 50 miles of the location of the proposed YMR within the last 80,000 years, which would imply a volcanic occurrence rate (in the area) of about 3/80,000 years = 3.75×10^{-5}/yr, while the USDOE was using an occurrence rate of 1 in 70 million years, or about 1.4×10^{-8}/yr.

Neither of these claims tells the whole story; they are arguments in the on-going risk discourse over the YMR. For both claims, one should ask, "How applicable is this piece of information to the future performance of the YMR?" Does the corrosion behavior of a piece of metal tell a compelling story for the performance of a similar (but not the same) metal in different temperature and chemical environments? Could a volcanic eruption 50 miles from the YMR have a significant effect on the YMR's performance? What should be our assessment of these issues, if different experts disagree about the answers?

4.1.2 Concerns about Decision-Making Processes and Perceptions of Radioactivity

In addition to scientific uncertainty and disagreements, there have been concerns about societal decision-making processes employed for HLW management that may not address all stakeholders' values and priorities. While the US is more advanced than any other country in its national HLW disposal program, the acceptance rate of the program by the host community, the state of Nevada, is low. Other countries, such as Finland and Sweden, while not as advanced in their programs, have achieved a much higher acceptance rate among potential host communities.

A key difference between the US and Finland or Sweden seems to lie in the process[19] that each country used to identify one or more host sites.

In addition, the word and concept of "radioactivity" is commonly used as an analogy for anything untouchable, the paragon of 'bad,' perhaps because of the association in many minds with nuclear bombs ([Slovic, 1993]; [Sjöberg, 2004]). "It's radioactive" is used in common parlance to describe anything that is physically or politically undesirable in the extreme[20]. There is a long-standing debate about whether or not risk perceptions about radioactivity are well-founded, and whether these perceptions can and/or should be changed through aggressive education campaigns. These debates are outside the scope of this thesis[21]. We are merely reminding the reader of the environmental context within which public discourse on HLW repository risk takes place.

4.1.3 Productive Public Risk Discourse

Despite this challenging background, there is hope that the situation can be improved. The recent successes in Finland and Sweden, and other positive experiences with risky societal decisions (e.g., examples in [NRC, 1996]), provide inspiration. One of the keys to the successful siting decision in Finland with the support of the local host community was the Environmental Impact Assessment (EIA) procedure implemented between 1997 and 1999 [Vira, 2004]. This EIA program focused on issues and concerns of greatest importance to stakeholder groups. This included an explicit *discussion of alternatives* in addition to safety assessments of the proposed

[19] Reasons for acceptance are complex, of course. For example, [Sjöberg, 2004] found that *perceived need for nuclear power* is also important in the case of acceptance by localities in Sweden, while a recent study in the US [Ansolabehere et al., 2003] shows that it does not play a role for local acceptance by hypothetical host communities in the US. Regardless of all the other factors that are important for acceptance, it is generally agreed that the decision-making process is one of the most important factors (see [Sjöberg, 2004], [NEA, 2003], or [La Porte and Metlay, 1996] for examples).

[20] In one example, a recent newspaper article referred to an under-performing basketball player as follows: "Young Stan had minimal offensive ability, handled the ball as if it was radioactive," [Reusse, 2004].

[21] Those interested could refer to the papers in the *Reliability Engineering and System Safety* special issue on "Risk Perception versus Risk Analysis" [RESS 1998]; Justice Breyer's book, *Breaking the Vicious Circle* [Breyer, 1993]; and "Risk Perception and Decision" contributions in *Risk, Democratic Citizenship, and Public Policy* [Weale et al., 2002].

repository. "In practice this meant that instead of discussion of the absolute risks of geologic disposal the focus was placed on the relative risk of the proposed project vs. the zero alternative," [Vira, 2004, p. 71]. Such *alternatives assessments* are an important part of the context for PA results and HLW management decisions. Many scholars and risk-management practitioners propose that safety/risk assessments *within* alternatives assessments framed by a wide group of stakeholders is the only way to solve problems such as HLW management in a democratic society [NRC, 1996; Strydom, 2002; O'Brien, 2000]. We note that in the US, the USEPA's Environmental Impact Statement (EIS)[22] (which is required for government projects) has a similar framework to the EIA used in other OECD countries.

One thing is clear based on the lessons from these past successes: we need a public risk discourse on HLW repositories that is more productive in resolving disagreements and building societal confidence. One starting place is to address the concerns of public citizens and stakeholder groups, particularly the local host communities, in continued dialog, as this has been a key to past successes [NEA, 2003]. In this chapter, we will explore how risk information can be used to address some of the stakeholder concerns in an effort to generate more productive discourse. There are many stakeholders in HLW management, and the two largest groups (other than the repository developer and regulators) are the local host communities, and the waste producers. We will focus on the concerns of the host community for the example application.

Risk information, primarily from PAs, can be used in a variety of contexts for HLW repositories, including: (1) choosing a host site, (2) choosing a design for the repository system, (3) licensing (construction and operation), (4) prioritizing research activities, and (5) making a convincing safety case to society. It has been proposed [Jenkins-Smith and Silva, 1998], and is fairly well accepted, that there are at least three important distinct, yet interrelated uses for PAs:

[22] Although the procedural implementation of the USDOE's EIS for the YMR was completely different than the Finnish case; in particular, the Finnish execution of the EIA involved extensive iterative dialog with stakeholders about what concerned them, while for the USDOE's EIS stakeholder concerns were not excplicitly elicited and addressed.

(1) regulatory compliance demonstration, (2) research prioritization, and (3) risk discourse among stakeholders. Each of these uses implies different requirements from the PA. In this chapter, we are focusing on the use of risk information from PAs for the third purpose, informing stakeholder risk discourse, although this is linked to the first two as well; certainly prioritization of research activities and regulatory compliance will inform and will be informed by public risk discourse.

The purpose of this chapter is to explore how risk from a HLW repository should be characterized for arguments in productive risk discourse. First, we present the US National Research Council's proposed analytic-deliberative process for democratic decision-making about risky societal projects, as this is a good theoretical basis for identifying what is needed in a public risk discourse. We follow this with a case study, the proposed US HLW repository, YMR in Nevada. We present some of the stakeholders' specific concerns about the YMR based on published opinion pieces, comments during federal rule-making, the State of Nevada's formal objections submitted to US Congress and lawsuits filed with a US federal circuit court of appeals, and other extensive public communications among key stakeholders (primarily the US Department of Energy (USDOE), the US Nuclear Regulatory Commission (USNRC), the US Environmental Protection Agency (USEPA), the State of Nevada (NV), and the NV Nuclear Waste Project Office (NWPO).) We end by demonstrating how YMR risk information could be used to address these stakeholder concerns, and discuss the potential contribution to future stakeholder dialog.

4.2 The Analytic-Deliberative Process for Making Societal Decisions

4.2.1 National Research Council's Risk Characterization Studies

The US National Research Council (NRC) has published a series of studies on how to improve decisions about risks to public health and safety and the environment

([NRC, 1983]; [NRC, 1989]; [NRC, 1996]). The most recent one, published in 1996, describes the analytic-deliberative process for making important societal decisions that involve public risks. Analysis and deliberation are defined as follows [NRC, 1996, p. 16]:

> *Analysis* includes various ways of reasoning and drawing conclusions by systematically applying theories and methods from natural science, social science, engineering, decision science, logic, mathematics, and law. *Deliberation* includes the methods by which people build understanding or reach consensus through discussion, reflection, persuasion, and other forms of communication—processes that allow for interaction across different groups of experts and between experts and others. Both analysis and deliberation are essential... deliberation frames analysis and analysis informs deliberation.

Two key ideas from the 1996 study are that: (1) risk characterization should be a *decision-driven* activity, (2) the history of decision-making about societal risks shows that involving a diverse group of stakeholders in analytic-deliberative processes often leads to more effective and efficient decisions about risky activities (as noted above) [NRC, 1996].

In the US, many of the decisions have already been made in the HLW repository program, as noted above. There are nonetheless many more decisions to be made, and opportunities to engage stakeholders in the analytic-deliberative process. Examples include creating a more productive dialog during the repository licensing hearings, and for effective and efficient negotiations in the on-going HLW transportation plans. In order to increase the productivity of risk information in stakeholder discourse about HLW repositories, the first step is to determine *what risk information* we need, since risk characterization that does not capture stakeholder concerns is not useful in the public discourse. What risk information we need is, in turn, determined by what concerns the stakeholders in HLW management. The purpose of the improved risk characterization is to (1) improve the discourse by explicitly engaging stakeholders about risk end-points and issues of concern to them, and in doing so, (2) improve stakeholder trust in the decision-making process for HLW management. In the US, there is extensive documentation in the public literature on stakeholder concerns both for risk in general, and on HLW repositories specifically.

4.2.2 Risk-Informed Deliberation – Lessons from Past Experience

The NRC-recommended analytic-deliberative process has been used in past pilot studies on how to resolve complicated societal risk problems. The lessons learned from these past studies give us an idea of how the risk analysis results described in this chapter could be used in the overall process. In one application, the analytic-deliberative process was used for a pilot study to pick an environmental remediation alternative at a contaminated USDOE site [Apostolakis and Pickett, 1998]. In that study, the results from the "analysis" part were found to contribute to: "(1) focusing on the interests of the stakeholders, (2) prioritizing the most important risks, as perceived/valued by the stakeholders, (3) providing a starting point for the generation of creative alternatives" [Apostolakis and Pickett, 1998, p. 632]. The analysts concluded that "The principal results of the analysis, the ranking of alternatives for each stakeholder, and the major contributors to these rankings were key to focusing the deliberation on what was important to the stakeholders and, thus, they contributed to the consensus-building process." While we have not discussed the stakeholders' evaluation of alternatives explicitly for different YMR decisions, this is nonetheless a key point. Taking into account the risk end-points that YMR stakeholders care about enables (1) focusing deliberation on what is important to stakeholders, and should eventually contribute to building consensus on what is acceptable, and what needs to be studied and/or resolved in the future, and (2) should contribute to building trust in the decision-making process.

In another pilot application, for the development of a risk-informed, performance-based regulatory system for USDOE facilities ([Rempe et al., 1999; Ghosh, 2000]), we learned other useful lessons. Interesting insights included: (1) the explicit elicitation of stakeholder concerns and representation of risk results contributes to *transparency* in the process, one of the keys to generating trust among stakeholders; (2) explicit discussion of stakeholder concerns and aspects of risk can contribute significantly to consensus-building by dispelling trivial disagreements, for example, based merely on differing nomenclature for the same thing, or using the same thing to mean different things.

4.3 Dimensions of Public Concerns about Risk in General

4.3.1 Risk Valuation

Numerous scholars have produced a rich body of studies about dimensions of *risk* that contribute to people's evaluation of its importance (for example, see [Slovic et al., 1980]). Scholars have also shown that risk is an imprecise word that people use to mean a variety of things. For our purposes, we are defining risk in terms of the triplet concept [Kaplan and Garrick 1981] that incorporates both the range of potential consequences from a particular decision/activity as well the probabilities associated with realizing different possible consequences, since this is better able to capture aspects of risk important to stakeholders.

Slovic's psychometric model introduced the notion of "dread" and demonstrated through empirical studies how people's valuation of risk increases with feelings of dread [Slovic et al., 1980]. Among the important dimensions of dread that figure into people's risk valuations are: (1) *Potential for catastrophe*, i.e., high-adverse-consequence events, for a cluster of victims in time/space. People want to know, is there a possibility of catastrophe? Even when the probability of this is very low, it seems that many people consider this in evaluating the risk associated with different activities. Dread increases with the potential for catastrophe. (2) *Controllability and measurability.* What kind of controls are there on the risk (and who or what has the control)? Are there ways to measure the risks (and who can measure it)? Dread increases as control and/or measurability decrease. (3) *Uncertainty.* How well do experts understand the risks? More on this under "public concerns about risk evaluations" below. Dread increases as uncertainty increases. A fourth important dimension of risk valuation is (4) *Equity Concerns.* How will the risk be distributed? Who is likely to suffer the consequences, and who benefits from the risky activity? Will the risk receptors be aware of the risks to which they're exposed? [Shrader-Frechette, 1993] Risk undesirability increases when the risk is posed to individuals who are unaware of it and/or to those who do not reap the direct benefits from the risky activity.

The activity of HLW disposal does poorly on all four of these risk dimensions: (1) there is a perceived potential for catastrophe (discussed in the next section), (2) there is a perceived lack of control and measure for people living near the repository in the distant future, (3) perceived uncertainty in expert assessment is high, and (4) many feel that both the risk-benefit distribution and likely unawareness of the future risk-receptors are unfair. Concerns in the second and fourth categories, while important, are outside the scope of this chapter. We will address, however, how to improve the dialog for the "potential catastrophe" and "uncertainty" risk dimensions.

4.3.2 Experts' Risk Assessments

Many scholars (see for example, [Jasanoff, 1998]) have raised the issue that scientists and experts are biased and these biases need to be taken into account when considering how to use their judgments, as encompassed in risk assessments for example. There are numerous mechanisms that can bias scientists' work [Cooke, 1991]. Institutional affiliations are one source of bias. It's not a surprise that there is widespread disagreement among findings from risk assessments conducted by industry analysts versus university professors or regulators. Stephen Gould's investigations into early scientists' work on human intelligence showed how the scientists' preconceived notions about their subjects severely biased their findings [Gould, 1996]; this is another source of bias, the selective use of information and uncertainty that resonates with preconceived ideas. Janis' seminal work on groupthink [Janis, 1982] exemplifies another possible mechanism for expert bias, the powerful drive for conformity in some small groups. The complex modeling exercise required for HLW repositories, particularly with the assumptions and inferences that are necessary (and may be hidden), amplifies these concerns about risk assessments.

4.4 Specific Concerns for the Yucca Mountain HLW Repository

We can review stakeholders' concerns about the YMR and see whether there is potential to address them using risk information, or at least whether we can build a more productive discourse by providing salient risk information.

We have compiled below many of the concerns expressed by stakeholders and external expert evaluators in public documents; the list is not comprehensive, but rather a representative group of concerns used for our illustrative purposes. We have gathered these from three kinds of sources: (1) the public comments contributed during federal rule-making, (2) the State of Nevada's statements, letters, and lawsuits over the YMR, and (3) formal and informal peer-review and advisory boards' published reports and papers.

In the US, the public has a chance to comment on federal rules before they become part of the regulatory regime. All public comments are recorded and the federal agency must address these comments in writing before, or at the time, the final rule is published [APA §533]. Thus, the YMR has an extensive record of public comments during federal rule-making since there have been three rules promulgated specifically for Yucca Mountain—(1) the USEPA's radiological protection standards [40 CFR 197], (2) the USNRC's implementation of the USEPA's standards[23] [10 CFR 63], and (3) the USDOE's siting criteria [10 CFR 963]; and three federal rules (standards [40 CFR 191], implementation [10 CFR 60], and siting criteria [10 CFR 960])

[23] These standards were ordered to be revised in the recent DC Court of Appeals ruling on July 9, 2004 [NEI v. EPA].

promulgated for HLW repositories in general before YM was chosen as the sole site to study. In this section, we highlight some of the concerns raised in the two rules most relevant for the YMR risk concerns: (1) the USEPA's 40 CFR 197, the radiological protection standards specifically for the YMR, and (2) the USNRC's 10 CFR 63, which specifies how the USNRC will implement the USEPA's 40 CFR 197 when regulating all YMR-related activities, including (most importantly) repository licensing, construction, and permanent closure.

In addition to contributing actively to the public comments during YMR federal rule making, the State of Nevada has published numerous documents about their concerns about the YMR, and has filed four lawsuits over the YMR with the DC federal circuit court of appeals. The State of Nevada has special status as the host community for the repository. We have included some of their additional risk-relevant concerns here, based on their published documents and lawsuits.

- **Compliance period.** The State of Nevada and other public comments to 10 CFR 63 and 40 CFR 197 contend that there is no defendable basis for using 10,000 years post-closure as the compliance period. They propose instead to use a time period that would include the time of maximum dose delivered to the RMEI/critical group. This was also the recommendation of the NRC in its guidance to the USEPA on technical bases for Yucca Mountain standards [NRC, 1995]. According to current dose projections, the time of maximum dose is most likely to be somewhere between 50,000 years and 500,000 years. The DC Federal Circuit Court of Appeals recently agreed with this argument and ordered the USEPA and USNRC to revise their rules in accordance with the NRC guidance [NEI v. EPA].
- **Compliance location.** Some comments expressed concern that the Waste Isolation Pilot Plant for transuranic waste in the US (WIPP) compliance point was 5 km from the WIPP repository, while the YMR compliance point is 18 km from the YMR [USEPA, 2001]. The

regulators specified the YMR compliance point according to the most likely nearest location of the critical group farming community, based on water availability and land characteristics[24]. But it is possible that there may be future inhabitants living closer than this point to the YMR, and drinking the groundwater but not farming with it; there is evidence that people have lived closer to the YMR intermittently in history. While this scenario is not part of the USDOE's TSPA (and the regulations do not require it), such a scenario can be explored with the USNRC's TPA code which has the optional feature to calculate drinking-water only doses to an individual drawing groundwater 10-km from the repository rather than 18-km from the repository.

- **Collective dose standards**. The WIPP compliance standards included both an individual dose standard as well as a cumulative release (in curies prescribed for each radionuclide) standard for the duration of the 10,000 year compliance period. The cumulative release standard was meant to be a proxy for limiting collective adverse health effects on people[25]. Some stakeholders expressed concern that there is no analogous collective (population) dose standard for Yucca Mountain [USNRC, 2001], although there is a groundwater protection standard that would limit the effects from the normal evolution scenario. The regulators' reasoning is that meeting the individual dose standard should provide adequate protection for the hypothetical critical group as a whole, and protecting the critical group (who is most at risk) protects the population as a whole.

[24] The USNRC writes: "EPA's standards, which specify the location for the RMEI at 18 kilometers in the predominant direction of ground-water flow, is consistent with the most likely pathway for radiological exposure. This location is generally considered the nearest location to Yucca Mountain where farming activities can reasonably be expected to occur. At distances less than 18 km to the Yucca Mountain site, there is evidence of intermittent or temporary occupation in modern (historic) times in and around the site—for prospecting or ranching... There also are a number of Native American archeological sites reported throughout NTS closer to the site than the Lathrop Wells location. However, the literature indicates that these were never permanently occupied, and most were abandoned by the end of the 1800's. Overall, the literature suggest many reasons for the absence of permanent inhabitation at distances much closer than 18 km to the site—unfavorable agricultural conditions, inhospitable terrain, the scarcity of mineral resources, and limitations on water availability." [USNRC, 2001, p. 55753]

[25] The cumulative release could be a fair collective dose measure if the linear-no-threshold hypothesis for health effects is a good assumption, and the population density in the affected area is approximately constant in the future.

- **Total dose from numerous minor sources in the area.** Nevada citizens have raised the issue that Yucca Mountain, and the compliance point for the hypothetical RMEI, is located adjacent to the Nevada Test Site. As a result of the weapons testing programs there, the ground is contaminated with radionuclides in much of the site. In addition, the Beatty low-level radioactive waste site is nearby. There have been suggestions to calculate a total effective dose to the RMEI from all area sources, i.e., from the YMR, Nevada Test Site (NTS) contamination[26], and Beatty LLW disposal, rather than looking at each individually. The reasoning is that even if each source alone seems insignificant, they may become significant if taken as a whole. Note that the USEPA and USNRC address this issue in their response to public comments on 40 CFR 197 and 10 CFR 63; their reasoning is that the 15 mrem/yr standard for the YMR should be protective even if we consider the doses from other NTS sources, since it is just a fraction of the allowable 100 mrem/yr man-made dose standard – that would leave 85 mrem/yr allowable from other sources. While the total-dose-from-all-sources is a legitimate concern for which risk information could be collected, it is outside the scope of this thesis. We note that there are ongoing studies to discover and project the extent of contamination (and contamination migration) at the NTS (e.g., see on-going Lawrence Livermore National Laboratory studies [LLNL, 1997]; [Smith et al., 2003]), and the needed information for the total area-dose calculations should be available in the future.
- **Probability of igneous event.** There is concern that the probability of an igneous event at the YMR in the future is more likely than currently projected by the USDOE ([Guinn, 2002]; [NWTRB, 2003]). Studies are under way in the USDOE complex to better assess the probability of an igneous event occurring in the next 10,000 years.
- **Uncertainty.** There is concern that the uncertainty in risk assessments for the YMR is much larger than projected in current PAs (see for example [Guinn, 2002]; [IAEA/NEA, 2002]; [MacFarlane, 2003]; [NWTRB, 2003]; [NWTRB, 2004]; [Shrader-Frechette, 1993]), and

[26] From decades of underground tests of nuclear weapons.

there is concern about incompleteness. One former member of the NWTRB, in exasperation after his resignation, wrote in a newspaper editorial [Craig, 2004]:

> Unfortunately, designing the Yucca Mountain repository turned out to be far more complex than had been anticipated. There's been one surprise after another. Yucca Mountain was selected as the site because it is located in the desert, and it was thought the arid climate would keep the waste dry. It turns out the mountain is wet. It was thought that the water wouldn't move the waste underground very quickly. Wrong again. Water moves through the mountain so fast that in order to meet the regulatory requirements for isolation from the biosphere, the Department of Energy had to add better-engineered waste containment canisters to the design. It now turns out that those canisters are likely to corrode.

- **Risk Dilution.** There is a concern that sampling artificially large distributions from numerous uncertain parameters in PAs can dilute the calculated risk (IAEA/NEA, 2002]; [Mohanty and Codell, 2004]). The concern is the following: suppose the true values of three uncertain parameters lie roughly at their median, and the confluence of these three parameters' values in a small interval around their medians also happen to result in the highest risk from the repository. But, as with many parameters, suppose these parameters' distributions span three orders of magnitude around the median values because of epistemic uncertainty. Then, in the Monte Carlo Simulation (MCS), a significant number of the realizations will result in lower doses through the conjunction of parameter values that are far away from their true values that result in high doses. Since each realization is weighted equally in the MCS, the true risk is artificially diluted. The International Atomic Energy Agency/OECD Nuclear Energy Agency peer review team for the YMR PAs raised the issue of possible risk dilution [IAEA/NEA, 2002].

4.5 Risk Information that Encompasses YMR Stakeholder Concerns

Present PAs are focused on projecting performance that is relevant for comparison with the regulatory criteria. The main criterion is that the projected mean dose to the receptor must be below a threshold for the duration of the compliance period, currently the first 10,000 years[27] after repository closure. Whether or not the regulations require it, if there is risk information that would help resolve some of the current disputes over Yucca Mountain (or facilitate continued dialog), it is worthwhile to gather and share it in the public risk discourse. There is, in fact, available information that could, with little additional effort, address many of the stakeholder concerns.

To summarize, our goal here is to compile risk information for a more productive public discourse that will encompass the following concerns about the YMR: (1) potential for catastrophe, (2) dose projections further into the future than 10,000 years, (3) dose projection at a point closer than 18-km from the repository, (4) volcanism scenario, (5) collective dose projections, and (6) potential risk dilution and uncertainty in PAs. We will address each of these in turn.

The USNRC's total-system performance assessment (TPA) code for the YMR is a good tool for collecting some of the necessary risk information because of its inherent flexibility. The TPA 4.1j code, which we use for our examples below, allows the user to: (1) specify different durations for the simulation time, (2) specify one of two distances for the dose calculation points, and (3) check intermediate results in the PA, such as the cumulative release from different barriers in the repository system at the end of the simulation time (see [CNWRA, 2002] for a complete description of the TPA 4.1j code and its capabilities). The TPA 4.1j code is an out-dated code supported by an older underlying database (the code has been updated with new information), so the exact numbers presented here should not be construed as current assessments. Nonetheless, the code is useful for our purpose of illustrating how information extracted from existing PAs could improve the risk discourse.

We introduced the Strategic Partitioning of Assumption-Ranges and Consequences (SPARC) method in the previous chapter as a way to extract risk information from existing PAs.

[27] The regulatory compliance time period may be revised, as mentioned above.

We could use the SPARC method to address a lot of the stakeholder concerns. The specific application will depend on the concerns. One key difference between the application here and the example in the previous chapter is that the end state which defines the significant-consequence partitioning, will be defined by the stakeholder concerns rather than the regulatory criteria. We will use SPARC trees in conjunction with the USNRC's TPA 4.1j code, as well as TPA-based results on their own, to address the stakeholder concerns.

4.5.1 Potential for Catastrophe

Slovic's studies have shown that people actually take a richer risk topography into consideration when judging the undesirability of different risks (as discussed in Section 3). People want to know what catastrophic potential exists for a given activity, even if the associated probability is low. In fact similar reasoning forms the basis for the USEPA's regulatory criteria for the WIPP, the US transuranic waste disposal site; the criterion there was a limit on the CCDF for the cumulative release of radionuclides (over the 10,000 year compliance time period), as follows [40 CFR 191.13(a)]:

> Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall: (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (appendix A); and (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (appendix A)."

Similarly, the UK has developed guidance for risky activities that places goals on the CCDF for consequences from risk activities. While the YMR regulations place a quantitative limit on the expected dose only, for the sake of discussion with concerned stakeholders, we could construct dose CCDFs for the YMR as well. The purpose is to see (1) whether circumstances exist that could lead to a *substantially increased dose* (SID) compared to the low expected doses in current

PAs, and (2) what confluence of uncertain parameter-assumption ranges (as will be sought with the SPARC method) or disruptive-event scenarios could lead to these SIDs.

4.5.2 Beyond the Regulatory Compliance Period – Risk for 100,000 Years after Closure

Figure 4.1 shows the 'spaghetti' curves for the base-case dose projection for the 20-km[28] receptor for 100,000 years[29], and Figure 4.2 shows the summary measures for the same base-case. Figure 4.3 shows the CCDF for the peak-dose; the peak dose for each realization is the highest annual dose achieved within the 100,000-year simulation time period[30]. We observe in Figure 4.2 that, in the 100,000 year time frame, the mean dose projection from the PA does cross the 15-mrem/yr limit at roughly 77,000 years. The CCDF in Figure 4.3 shows that about 20% of the realizations result in a peak dose that exceeds the regulatory limit for the mean; the mean dose is driven by the top fifth of the distribution of doses (this is also seen in Figure 4.2, where the mean curve is close to the 95th percentile curve). In extreme situations, such as the upper 5% of the dose distribution, the dose exceeds 200 mrem/yr, which is more than 13 times the regulatory limit. We see that considering a time frame greater than 10,000 years results in a much higher instance of SIDs. In the 10,000-year time frame, the base case shows that it is nearly impossible to get a dose of 15 mrem/yr to the 20-km receptor. In 10,000 years (the first tenth of the dose projection in Figures 4.1 and 4.2), the peak mean dose was only ~0.08 mrem/yr, and the 95th percentile was ~0.2 mrem/yr. Extending the time under consideration to 100,000 years increases the peak of the mean dose by more than 2 orders of magnitude, and increases the 95th percentile dose by 3 orders of magnitude.

[28] The TPA 4.1j code was developed before the final EPA rule (40 CFR 197) specified 18-km as the distance to the dose receptor. The updated TPA code has 18-km as the default choice. For our illustrative purposes, the 20-km dose is good enough. The dose to the 18-km receptor would be slightly higher than those projected for the 20-km receptor.
[29] We stopped at 100,000 years because this older version of the TPA code is significantly less reliable in longer time periods.
[30] For example, in the worst realization (the top 'spaghetti' strand on the right side of the plot), the peak dose achieved is ~0.7 rem/yr or 700 mrem/yr at ~77,000 years.

The next step is to seek an explanation for why the repository delivers SID in some cases and not others in the realm of possibilities. We can use the SPARC method for this. We use a 100-mrem/yr dose as the partitioning point this time, since we are searching for outlier scenarios that result in the worst SIDs; the 15 mrem/yr dose is too low as a threshold for 100,000 years since the average dose is increased significantly compared to the 10,000 year case.

We applied the SPARC method in this case in the same way we did in the previous chapter. Once again, we found that we could explain a significant fraction of the SID cases with just a handful of significant parameter-assumption ranges as "savior attributes." The PSFDM is a key uncertain parameter for this case too. Figure 4.4 shows the CDF-partitioning for the PSFDM. The x-axis is the PSFDM value, and y-axis is the cumulative distribution function (CDF). This figure shows the results for two runs of 500 base-case realizations. Of these 1,000 total realizations, 90 produced SIDs (annual dose in excess of 100 mrem/yr). The dashed black line shows the CDF of the PSFDM values in the 90 SID realizations, and the solid grey lines shows the CDF of the PSFDM values in the 910 non-SID realizations. In multiple runs of 500 base-case realizations *and* more focused testing of SID-producing confluence of parameter-assumption ranges, we observe no SID realizations at values of PSFDM within the first 52% of its distribution. So the uncertainty in this parameter alone can explain 52%/91% (of all realizations were non-SID) = 57% of the non-SID realizations, and is clearly potentially a high-worth savior attribute. We also found that a key WP corrosion parameter, AA_1_1, also acts as a savior attribute if its true value lies in the first 24% of its distribution. Figure 4.5 shows the CDF-partitioning for the AA_1_1 parameter. In multiple 500-realization base cases and more focused test cases, we observed no SID cases at values within the first 24% of its distribution. So these two parameters alone could explain (0.52+0.24 -0.52*0.24)/0.91 = ~70% of the non-SID realizations. In addition, if the waste package flow factor or the subarea wet percent is within the first 6% of their respective distributions, there is a high probability of no SID cases.

There were also some parameters that acted as savior attributes in concert. For example, Figure 4.6 shows a box plot of sampled values of DTFFAVIF and ARDSAVNp in SIDs vs. normal cases. If the distance to the tuff-alluvium interface (DTFFAVIF) is not too large (within the first 70% of its distribution) *and* the retardation factor for Neptunium in alluvium turns out to be on the high side of its distribution (in the top 36% of its distribution) at the same time, these together act as a savior attribute, and could explain about (0.7*0.36)/0.91 = ~27% of the non-SID cases. Figure 4.7 shows the SPARC tree summarizing the savior attributes for the 100,000 year 20-km dose projections. About 20% of the non-SID cases are not explained by these savior attributes alone; they require looking at higher order explanations, e.g., 5 or 6 repository attributes working together to keep the dose low, as the repository is designed to do through its multi-barrier system.

4.5.3 Compliance Location Sensitivity – Dose Receptor at 10-km from the Repository

Figure 4.8 shows the CCDF for peak doses to the 10-km receptor within 10,000 years. Almost 5% of the realizations achieve a peak dose greater than 15 mrem/yr. In the previous chapter we presented the SPARC results for the 10,000 year 10-km receptor scenario, so we will not present the results again here.

Figure 4.9 shows the base-case dose projection for the 10-km receptor for a longer time period of 100,000 years, and Figure 4.10 shows the summary measures for this base-case. Figure 4.11 shows the CCDF for the peak-dose in this case. As expected, the 10-km doses are much higher than the 20-km doses – the peak of the mean dose is roughly an order of magnitude higher in the 10-km case. The 95th percentile climbs as high as 2 rem/yr, about 140 times the regulatory limit for the 18-km receptor. The CCDF is Figure 4.11 shows that about 70% of the realizations have a peak dose that exceeds 15 mrem/yr. Clearly, the base case scenario for the 10-km receptor for 100,000 years results in SIDs in the majority of possible situations, so we will not analyze this further with the SPARC method; the answer to "why" (for SID) in this case is merely the normal evolution of the repository under the majority of conceived assumption/parameter-ranges (thus the SPARC analyses, which is geared to low-probability "tail" scenarios, are not applicable here). It is worthwhile to keep in mind that the repository is designed to keep doses well below the 15 mrem/yr threshold for the current regulatory compliance period of 10,000 years and compliance location of 18-km; so it is not surprising that doses to a receptor substantially closer to the repository further in the future will exceed the regulatory threshold.

4.5.4 Risk from Disruptive Volcanism Scenario

The main disruptive scenarios for the YMR are: (1) *Human intrusion.* This is a stylized single borehole intrusion into the repository penetrating a single WP, as prescribed by the USEPA regulations (40 CFR 197); (2) *Faulting* (seismic). In this scenario, seismic disturbances cause rocks to fall on the drip shield/outer WP layer. If the rock impacts/overburden overcome the plastic strength of a WP, it is breached and its inventory becomes available for release; (3) *Igneous,* intrusive or extrusive (volcanic). In both cases, waste packages are breached by a volcanic plume, but in the intrusive scenario the inventory from WPs is available only for transport to groundwater below. The extrusive case is much more serious because radionuclides from breached WPs are brought to the groundsurface with the volcanic plume. As a result, the critical group gets very significant doses (between 1 and 100 rem/year, depending on the time of the event) from the radionuclides embedded in the ash plume covering the ground surface. We will concentrate on the igneous disruptive scenarios since these are driving the risk in the current YMR PAs. While human intrusion scenarios can result in substantially increased doses, particularly to the intruders, we will not address them here because (1) the human intrusion scenario is much more complicated in terms of the assumptions the analyst must make about the motives and technology of future intruders, (2) there is a qualitative difference between risk to active intruders versus passive risk receptors such as farmers who are exposed passively through their normal life activities, and (3) the lack of any known attractive mineral resources in the YM desert supports the assumption that human intrusion is unlikely[31]. Seismic scenarios are discussed in the next section.

Figure 4.12 shows the dose projection for the 20-km receptor, for a 100-realization volcano scenario. Figure 4.13 shows the summary measures for the same scenario. These are the *conditional* doses for the volcano scenario. We can see that the volcano scenario is one potential cause of a SID. In each of the 100 realizations, a volcano occurs at a random time within the 10,000 year time frame. The resulting dose from the disruptive event is added to the base-case dose. The bulk of the dose resulting from volcanic events is due to radionuclides that are carried by magma from breached WPs and deposited on the ground surface to irradiate critical-group members. The magma is much more effective as a vehicle for radionuclides to escape the repository and reach the accessible environment.

We can see from Figure 4.12 that the dose resulting from the volcanic event dominates the total dose in the igneous scenarios – the volcanic dose is orders of magnitude higher than what is achieved through the normal evolution of the repository. In Figure 4.12, the dose projection for each realization begins with the initial volcanic event, and the conditional dose to the 20-km receptor, *given a volcanic event*, is close to or greater than 1 rem/yr. This is almost four orders of magnitude higher than the 95th percentile (an upper bound) of what is achieved in the "base case"/normal evolution scenario in the first 10,000 years, as shown in Figure 4.1. The associated frequency of a volcanic event is currently assessed to be very low, on the order of 10^{-7}/yr, which would mean a 1/1000 chance that a volcano will occur within the first 10,000 years after closure. So the dose projection shown in Figure 4.13, which is *conditional* on a volcano actually occurring within the first 10,000 post-closure years, is for a most-likely low-probability scenario.

[31] Whereas the human intrusion scenario dominated risk in the case of the WIPP, since it is located in salt beds and salt is a known valuable mineral.

Volcanic scenarios are analyzed in both USDOE and USNRC PAs. The results are presented, however, as *weighted* dose projections; for example, if the assessed probability[32] of a volcano occurring in is 10^{-7}/yr, then the dose projections of the volcano scenario are multiplied by 10^{-7} and a conditional 1 rem/yr dose would be displayed as 10^{-7} rem/yr. We present the dose projections directly from the TPA 4.1j code without initial weighting for two reasons: (1) stakeholders are concerned about potential catastrophic events, and the consequences from possible future volcanoes certainly possess catastrophic consequences in this context; and (2) there are significant disagreements about the probability associated with the occurrence of volcanoes. Hence, it is useful to look at the potential conditional consequences initially independently of the associated probability, in the same vein as CCDFs displaying a full range of consequences, even those with very low probabilities. Figure 4.14 shows the CCDF for the conditional peak dose to the 20-km receptor from the volcano scenario, where a volcanic event occurs some time in the first 10,000 years after closure.

So what can we contribute to the discourse on the volcano scenario by explicitly considering the range of consequences? First, we can convert the dose projections to risk to get a better idea of what they mean in terms of risk. If we use the BEIR assumptions used by the NAS [NRC, 1995] for the technical bases for YM standards, the risk from cumulative lifetime dose (which is though to be the best risk estimator) is 5×10^{-4}/rem chance of early fatality, disease, or genetic defect. Using this conversion factor, the median lifetime risk from the volcano scenario for the 20-km receptor is[33] 7/2 rem/yr[34] x 5×10^{-4}/rem x 70 years = 12.5% chance of early fatality, disease, or genetic defect. While 0.125 lifetime risk would be unacceptable for a normal

[32] The probabilities have not been finalized yet.
[33] The doses drop quickly after the peak dose immediately following the volcanic event. So thisi s just a rough (most likely conservative) approximation of the average annual dose to someone living in the area for most of her life.
[34] 7 rem is an approximation of the median peak dose (based on the volcano scenario realizations shown in Figure 4.13) from the volcano scenario, and we divide this by two as an estimate of the average annual dose over the receptor's lifetime; this is just an approximation of the effect of the sharp drop-off from the peak-dose over the subsequent years after an eruption.

evolution scenario (where the target is ~10^{-5} lifetime risk), those concerned about the volcano scenario may find it acceptable for a low-probability 'catastrophic' disruptive scenario. Only in a few worst cases does the volcanic eruption produce peak doses that result in a very high probability of early death/disease (3 cases past 1,000 years where peak dose is ~100 rem/yr), and these truly catastrophic scenarios have a very low assessed probability, ~3/100 * 10^{-7}/yr = ~3×10^{-9}/yr. Even if the true probability is a couple of orders of magnitude higher, it would still be a low probability.

4.5.5 Collective Dose

As mentioned above, the proxy for collective dose calculations for the WIPP was the cumulative release to the accessible environment (5 km from the repository boundary) over the first 10,000 years after closure. We could use the same measure as a proxy for collective dose projections for the YMR. The cumulative release of radionuclides at the location of potential groundwater wells bounds the collective dose that is possible, since the radionuclides are the initial source term for the dose. Figure 4.15 shows the CCDF of cumulative release (from the important long-lived radionuclides Np-237, I-129, and Tc-99 only; unitless since release is normalized to USEPA limits) at the 20-km point in the saturated zone for the 10,000-year-time frame, and Figure 4.16 shows the same for the 100,000 year time frame. Figures 4.17 and 4.18 show the cumulative release (normalized to USEPA drinking water limits, e.g., a release of greater than 1 represents an unacceptable amount of release) to 10-km CCDF for 10,000 yrs and 100,000 yrs respectively.

For a point of comparison, we can take the USEPA drinking water guidelines that stipulate an acceptable Np-237 concentration for drinking water. For the representative groundwater volume assumed at the YMR (for the critical group located at 18-km from the repository) for annual withdrawal (3.7×10^{7} gallons/year), 5.5 Ci/yr of Np-237 would be required to reach the limit. The releases shown in Figures 4.15-4.18 are normalized to these limits. We see that for the 10,000-year case, neither the 10-km nor the 20-km cumulative release comes close to crossing these drinking water goals. For the 100,000 year case, about 4% of the realizations cross the goal for the 20-km receptor, and about 10% cross the goal for the 10-km receptor.

4.5.6 Potential Risk Dilution and Uncertainty in Risk Assessments

Risk dilution is a concern in PAs with hundreds of uncertain parameters, the uncertainties for some of which span several orders of magnitude in their respective distributions. The SPARC method directly addresses the risk dilution concern, since it systematically searches for the sample-domain where SIDs is possible, initially irrespective of the probability associated with the domain (as described in detail in the previous chapter). Hence SID scenarios with potentially artificially low probabilities would not be screened out of consideration in the SPARC analyses. By finding the sample domain capable of producing SIDs, we can further focus our studies into potential effects of incompleteness. Hidden assumptions in large complex analyses is another common concern about risk evaluations in uncertain modeling exercises ([Jasanoff, 1998]; [Shrader-Frechette, 1993]). The SPARC method addresses this concern too, by showing in the SPARC trees *how* the repository system may result in SIDs. For example, the SPARC tree in Figure 4.7 shows that for the 20-km receptor, SIDs (above 100 mrem/yr) are likely to result if the spent fuel dissolution rate is in the upper half of its assumed distribution, AND the corrosion rate is in the upper three quarters of its distribution, AND either the Np-237 retardation factor in Alluvium is in the upper three quarters of its distributions or the distance to the tuff-alluvium interface is in the upper 30% of its distribution, etc.

Trust in the group carrying out the analyses is of paramount importance when an individual or group evaluates how to use the information from risk analyses ([Jenkins-Smith and Silva, 1998]; [Sjöberg, 2004]; [La Porte and Metlay, 1996]). There are at least two broad categories of approaches to address the hidden-assumption issue: (1) rigorous, independent peer review by credible scientists and experts to bolster public confidence, and/or (2) methods that attempt to make analyses as transparent as possible to anyone who wishes to review the analyses. The second is significantly more difficult because of the complexity of PAs, but these methods are worth pursuing nonetheless because of their potential benefits. The SPARC trees contribute to transparency by explicitly uncovering and displaying the modeling assumptions that underlie repository risk, displaying the assumption-ranges that pose challenges to the repository system and the assumption-ranges that 'save' the repository system. In support of the first category, numerous findings by risk perception scholars [Slovic, 1993], scholars of WIPP history [Jenkins-Smith and Silva, 1998], and the history of quantitative risk analysis (QRA) in societal decision-making [Apostolakis, 2004] point to the need for extensive peer reviews by scientists who are (and are perceived to be) independent. This is certainly possible; in the 1998 surveys of New Mexico and continental US residents, NAS was found to have the highest credibility among members of the public, the majority perceiving NAS scientists to be neutral, "accurate, competent, and concerned" [Jenkins-Smith and Silva, 1998, p. 115].

4.6 Discussion

The public risk discourse about the proposed HLW repository in the US, the YMR, is somewhat fragmented and disjointed with stakeholders discussing different points of interest. There are clear benefits to improving the public risk discourse about HLW repositories. The opposition by the host community, the State of Nevada, has led to a taxed relationship between the State and the repository developer, the USDOE, with great inefficiencies incurred in the process. For example, negotiated rule-making at the start of the regulatory process might have avoided the recent costly lawsuits [NEI v. EPA] that resulted in a court-ordered revision of the radiological protection standard for the YMR. There may have been some unnecessary resource expenditure into designing a repository to meet the now-defunct standard. Another example of inefficiency is that the State of Nevada has been denying the USDOE water rights within the State, because of their opposition to the YMR. As a result, the USDOE is required to truck in water from neighboring states, and has created an artificial water reservoir, at an expense that would not have been necessary had they had local approval. The situation does not have to be this way; the HLW program successes in Finland and Sweden, and years of history in other projects in the US demonstrate that there is hope.

The NRC's analytic-deliberative process, which is implicitly used in the EIA framework in EU countries and the intention of the EIS process in the US, provides the theoretical basis for improving the risk discourse. In this chapter, we highlighted some stakeholder concerns about YMR risk that are not explicitly discussed in the official risk documents, and demonstrated how risk information could be extracted from existing PAs to address these concerns with little additional effort. There is a lot of information on the YMR that is not currently incorporated into the PAs, and there are not enough resources to incorporate *all* of this information into PAs. It is worthwhile, however, to search for those pieces of information that would contribute significantly to a public risk discourse that is more productive in resolving disagreements. We have tried to do that in our application. We found that concerns about (1) risks in longer time periods, (2) risks to dose receptors at different distances from the repository, (3) risk from volcanic scenarios, and (4) collective dose estimates, are readily informed by what we can obtain from existing PAs. Furthermore, the SPARC method introduced in the previous chapter can help display *how* these risks may be realized, and thus contribute to transparency.

Specific findings from our analyses for the YMR that could contribute to more productive public risk discourse by providing information on what stakeholders care about, include:

1. The risk dilution concern is addressed with the SPARC method since it identifies specifically what parameter/assumption ranges can result in SIDs, without weighing them by assumed

probability distributions first. Hence SID-producing scenarios are not screened out of consideration in the PAs through assumed low-probabilities.

2. Stakeholders who are interested in dose projections over longer time periods may be interested to know that even in the 100,000-year post-closure time frame, the SPARC method identified several repository savior attributes (for the 20-km receptor) that prevent SIDs (redefined as peak annual doses exceeding of 100 mrem/yr) with a high probability, such as PSFDM (key spent fuel dissolution rate) value in the lower half of its distribution (see Figure 4.7). Better characterization of this parameter, in terms of this strategic partition, could greatly increase confidence in the YMR. The CCDF for the peak dose (Figure 4.3) shows ~20% chance of exceeding 15 mrem/yr in 100,000 years post-closure, and hence ~80% chance of meeting the 15 mrem/yr threshold even in the 100,000-year time frame.

3. For those interested in future humans living closer to the YMR, we found that for the 10-km receptor, the 15 mrem/yr threshold is exceeded in (a) less than 5% of the cases in the 10,000 year time frame (Figure 4.8), but (b) more than 70% of the cases in the 100,000-year time frame (Figure 4.11) and that the projected mean dose to the 10-km receptor crosses 15 mrem/yr at approximately 50,000 years after closure (Figure 4.10). The 10-km receptor is not a required consideration in the regulations; this risk information could inform informal deliberation.

4. For those concerned about volcanic scenarios, which constitutes the potential "catastrophes" for the YMR, we showed the peak dose (to the 20-km receptor) from a volcano to lie between 0.4 and ~400 rem/yr (Figure 4.14), with a median of ~7 rem/yr. This corresponds to a median lifetime risk of 12.5% of early fatality, disease, or genetic defect. While 12.5% risk would be unacceptable for a normal evolution scenario, society may find it acceptable for a low-probability disruptive scenario. Only in the worst few cases does the lifetime risk climb to above 50%, and the associated probability of these catastrophic scenarios is vanishingly small, current estimates on the order of 10^{-9}/yr. The analysis here displays volcano doses

more transparently than current USDOE and USNRC analyses where the doses are shown weighted by their assumed point-estimate probabilities (which are highly uncertain).

5. The collective-dose estimates (calculated according to USEPA drinking water guidelines and analogous to the WIPP calculations) show that the individual dose criterion is indeed protective of the collective population; the collective dose thresholds are met in many more of the PA realizations than the individual dose threshold.

Figure 4.1 Combined Tc-99, I-129, Np-237 20-km Dose vs. Time, 200-Realization Base Case

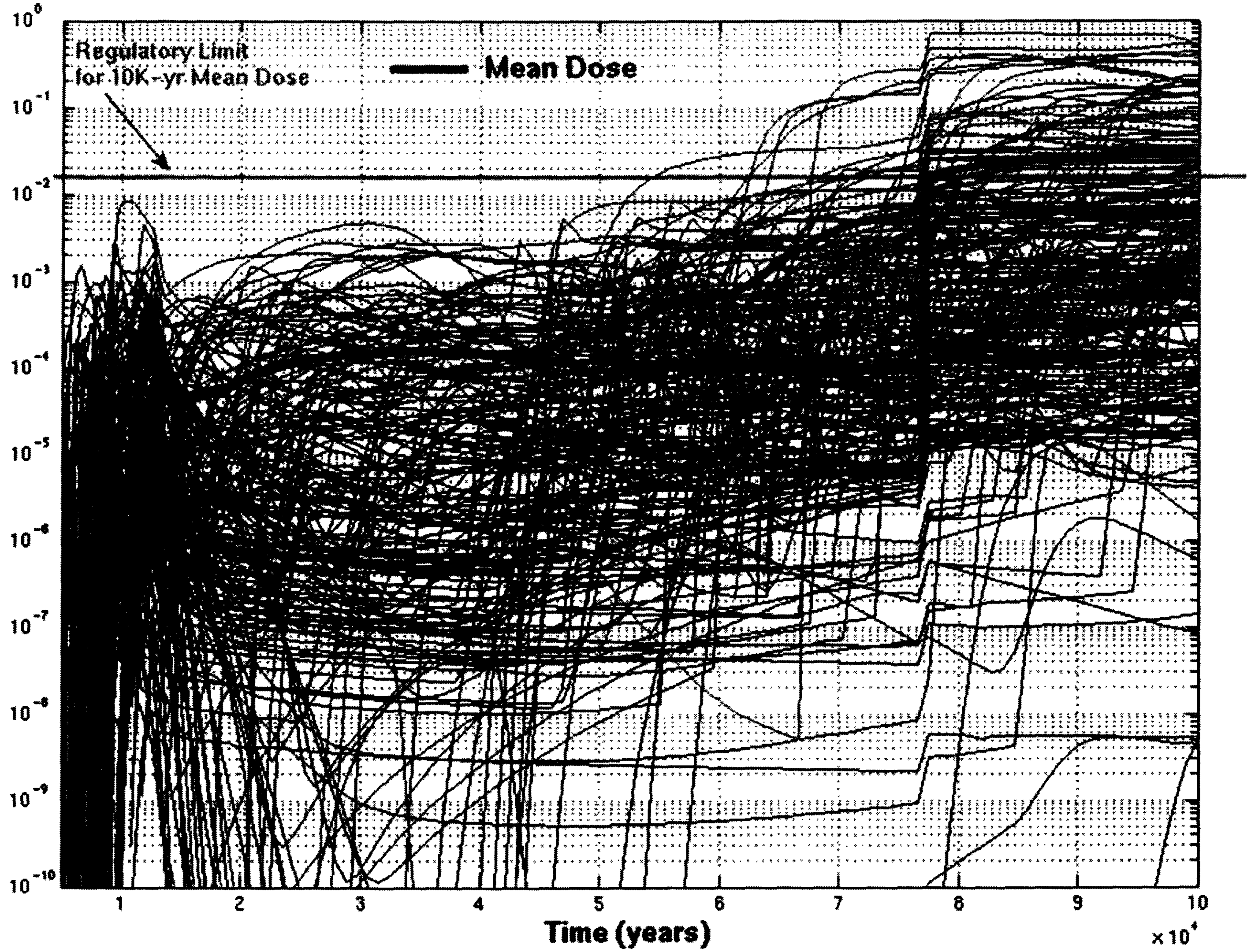
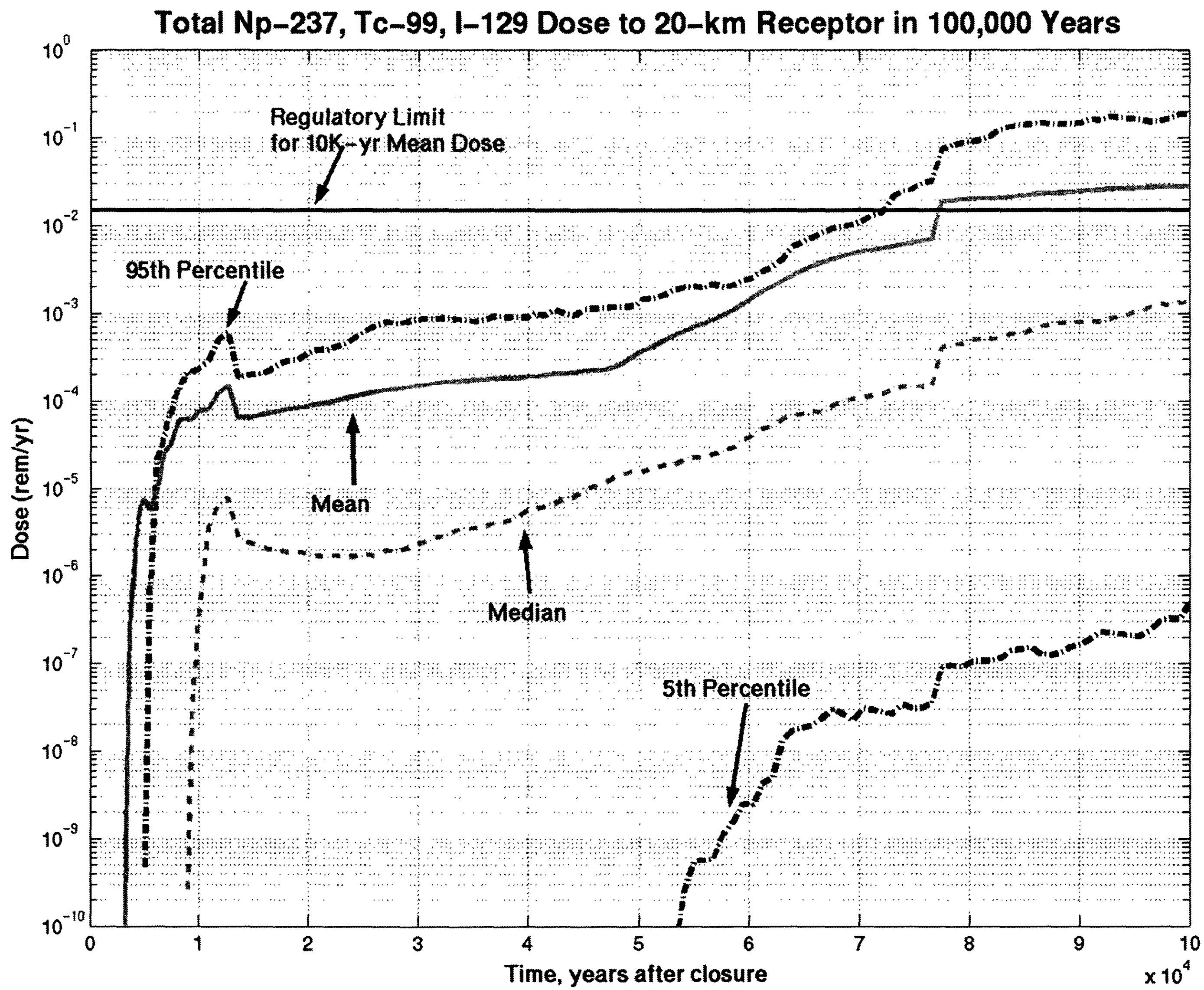
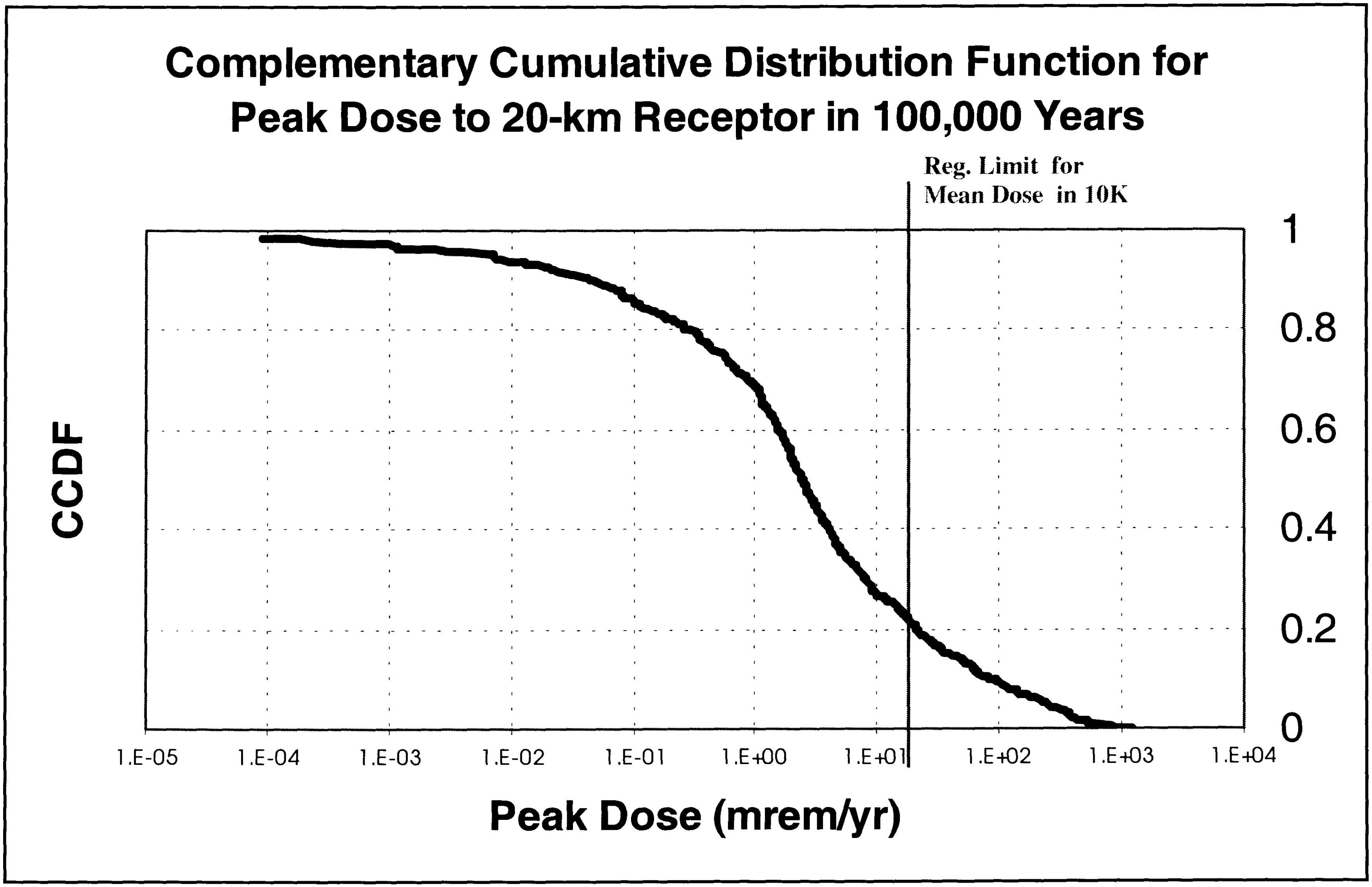


Figure 4.2



Total Np-237, Tc-99, I-129 Dose to 20-km Receptor in 100,000 Years
Regulatory Limit
for 10K-yr Mean Dose
95th Percentile
Mean
Median
5th Percentile
Dose (rem/yr)
Time, years after closure
x 10^4

Figure 4.3



Complementary Cumulative Distribution Function for
Peak Dose to 20-km Receptor in 100,000 Years
Reg. Limit for
Mean Dose in 10K
CCDF
1
0.8
0.6
0.4
0.2
0
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
Peak Dose (mrem/yr)

Figure 4.4
Cumulative Distribution Function for Key Parameter in Spent Fuel Dissolution Model (PSFDM1), Dose to 20-km Receptor in 100,000 years, using 100 mrem/yr Partitioning Criterion; failure CDF in solid

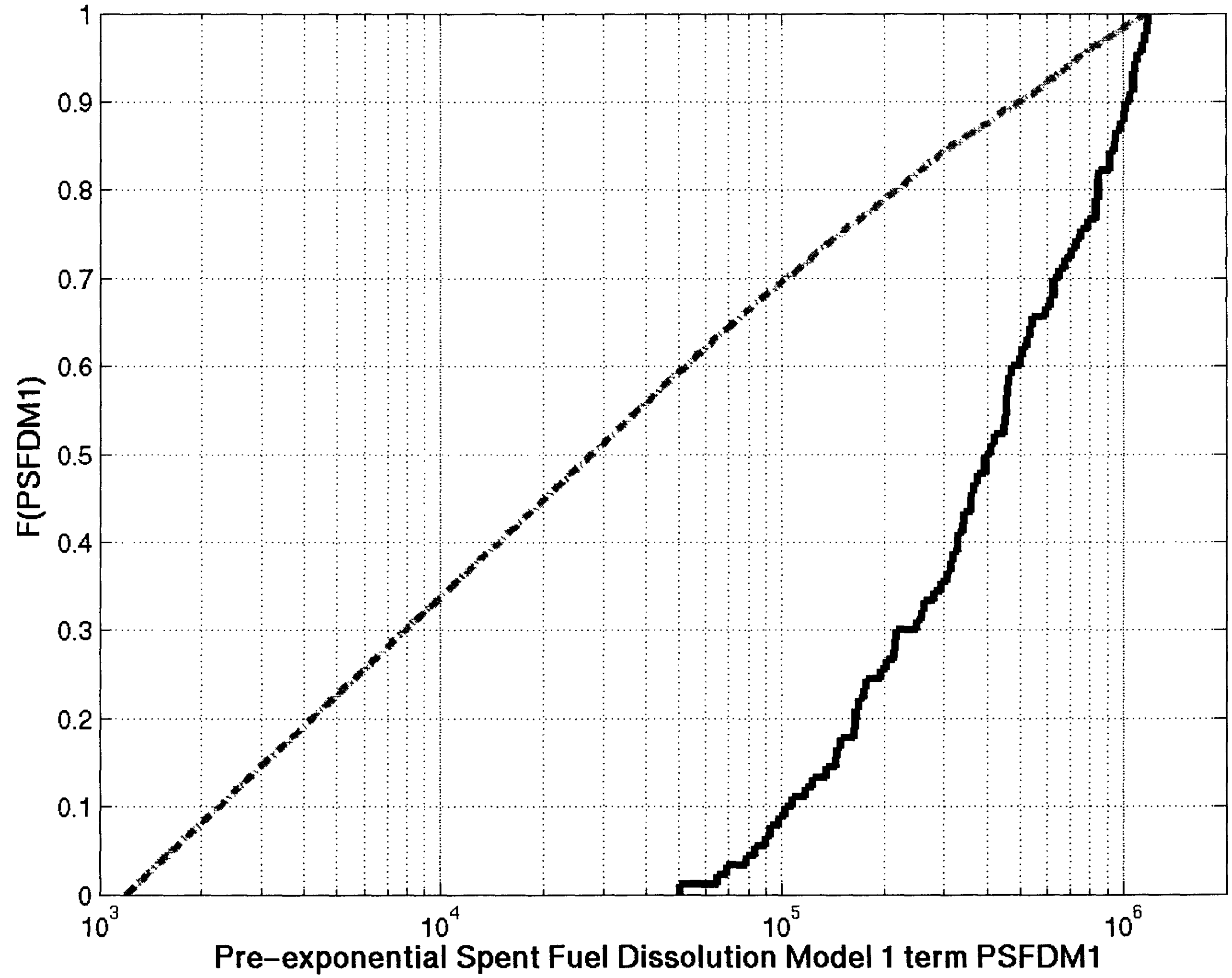


Figure 4.5

Cumulative Distribution Functions for Key WP Corrosion Parameter AA11, Dose to 20-km Receptor in 100,000 Years, using 100 mrem/yr Partitioning Criterion; failure CDF in solid

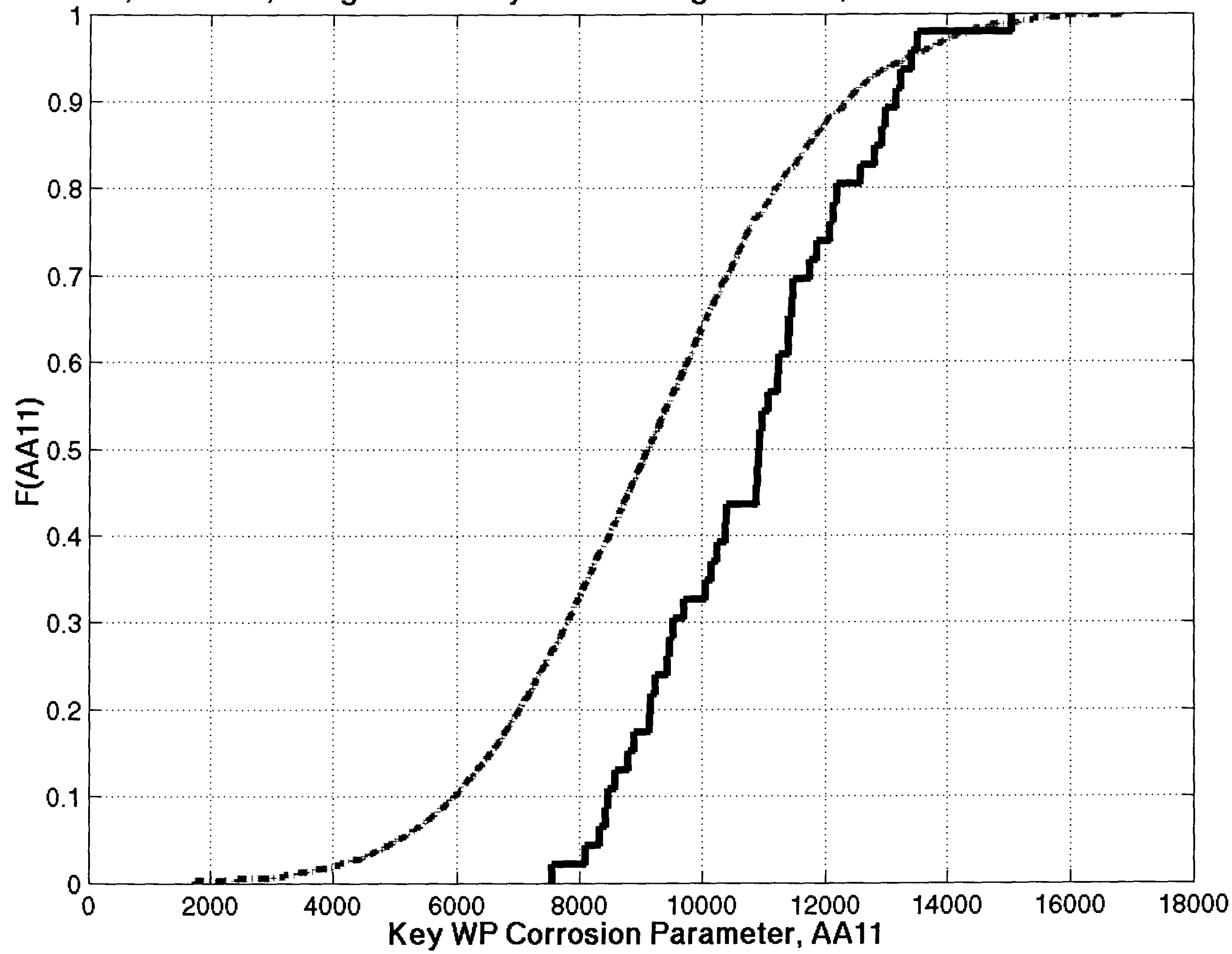


Figure 4.6

Plot of Failures (black triangles) and Successes (grey circles), for 20-km Receptor in 100,000 years, using 100 mrem/yr Partitioning Criterion

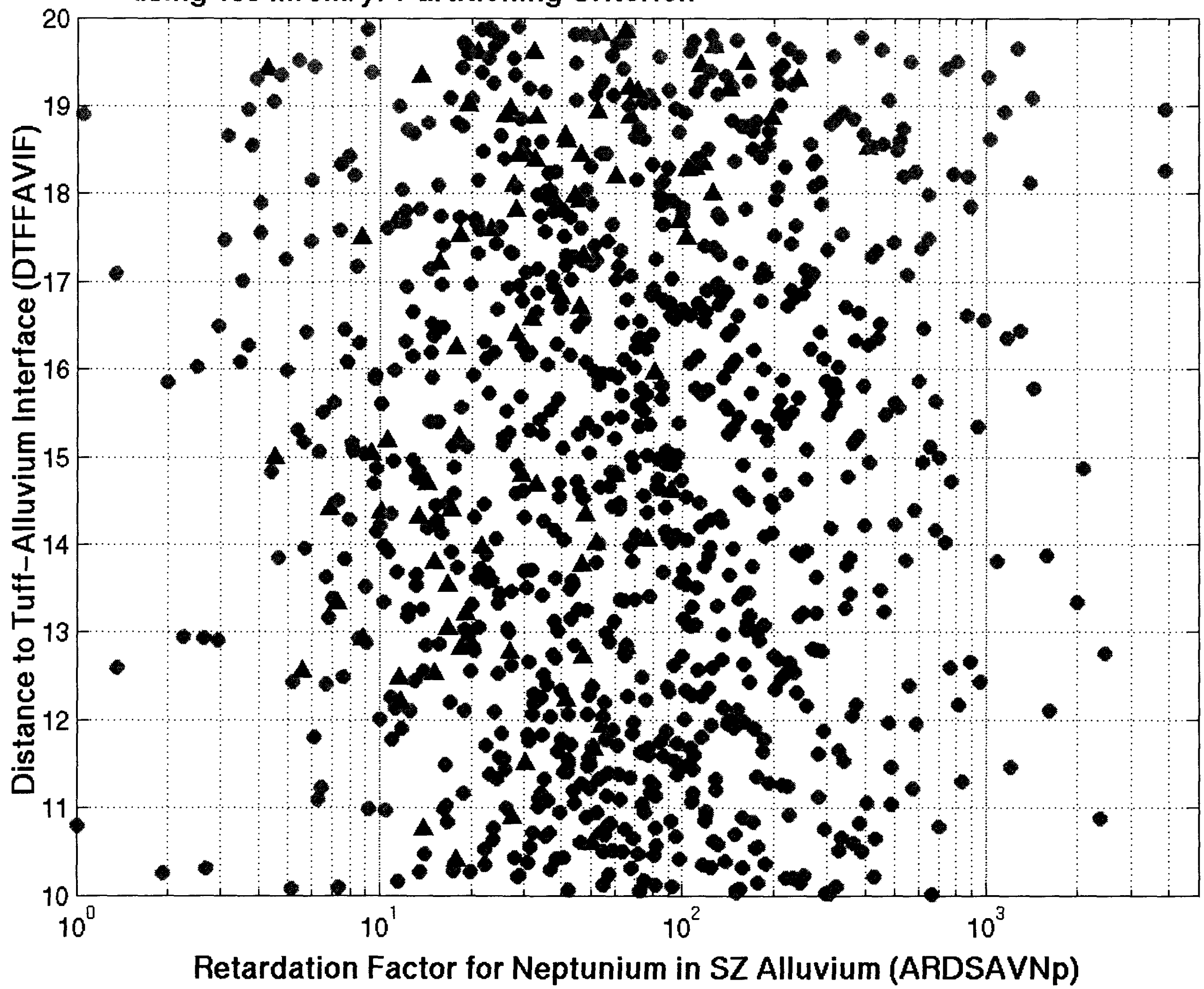


Figure 4.7 SPARC Tree for 20-km Receptor, SID of 100 mrem/yr within 100,000 yrs

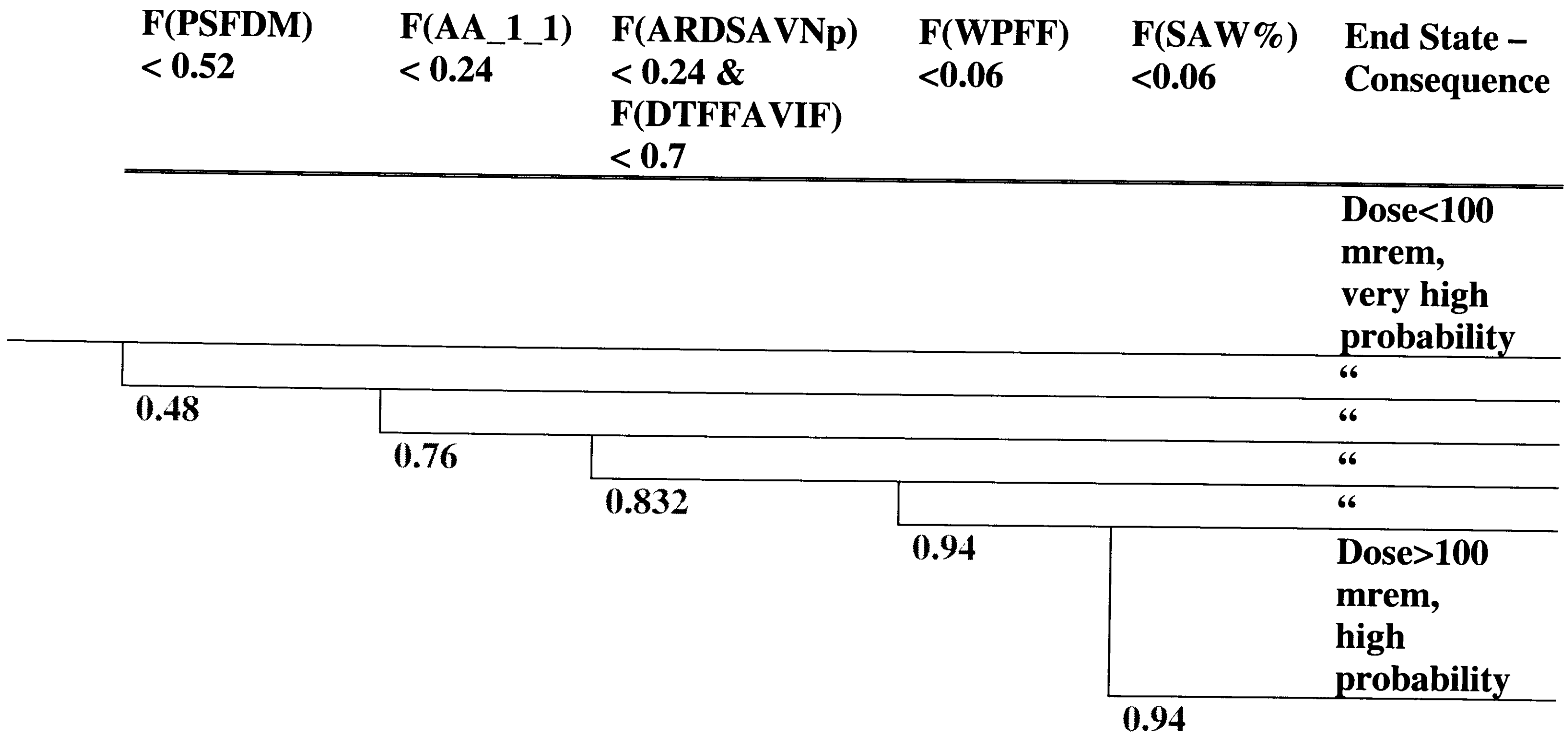
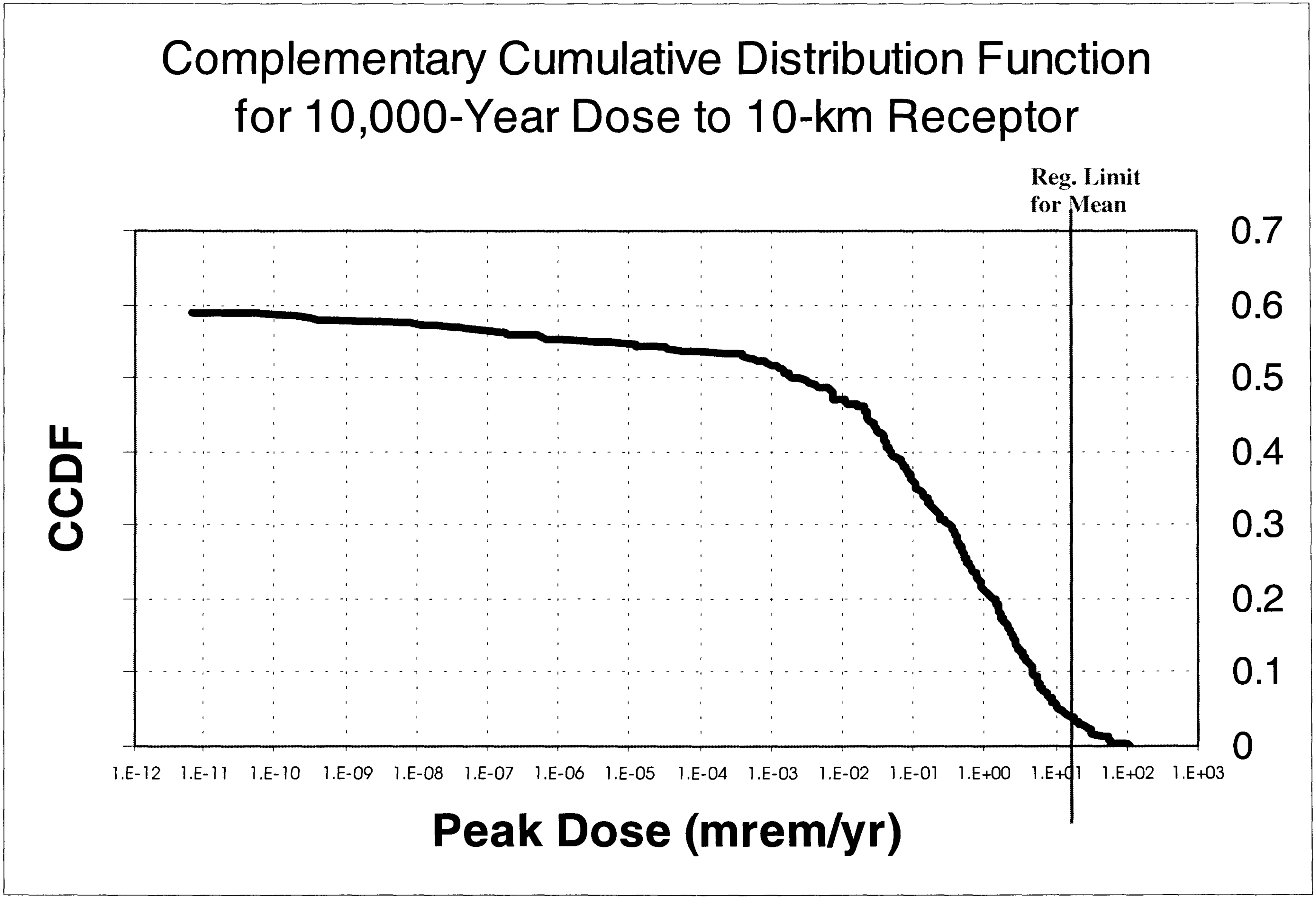


Figure 4.8



Complementary Cumulative Distribution Function
for 10,000-Year Dose to 10-km Receptor
Reg. Limit
for Mean
CCDF
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.E-12
1.E-11
1.E-10
1.E-09
1.E-08
1.E-07
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
Peak Dose (mrem/yr)

Figure 4.9

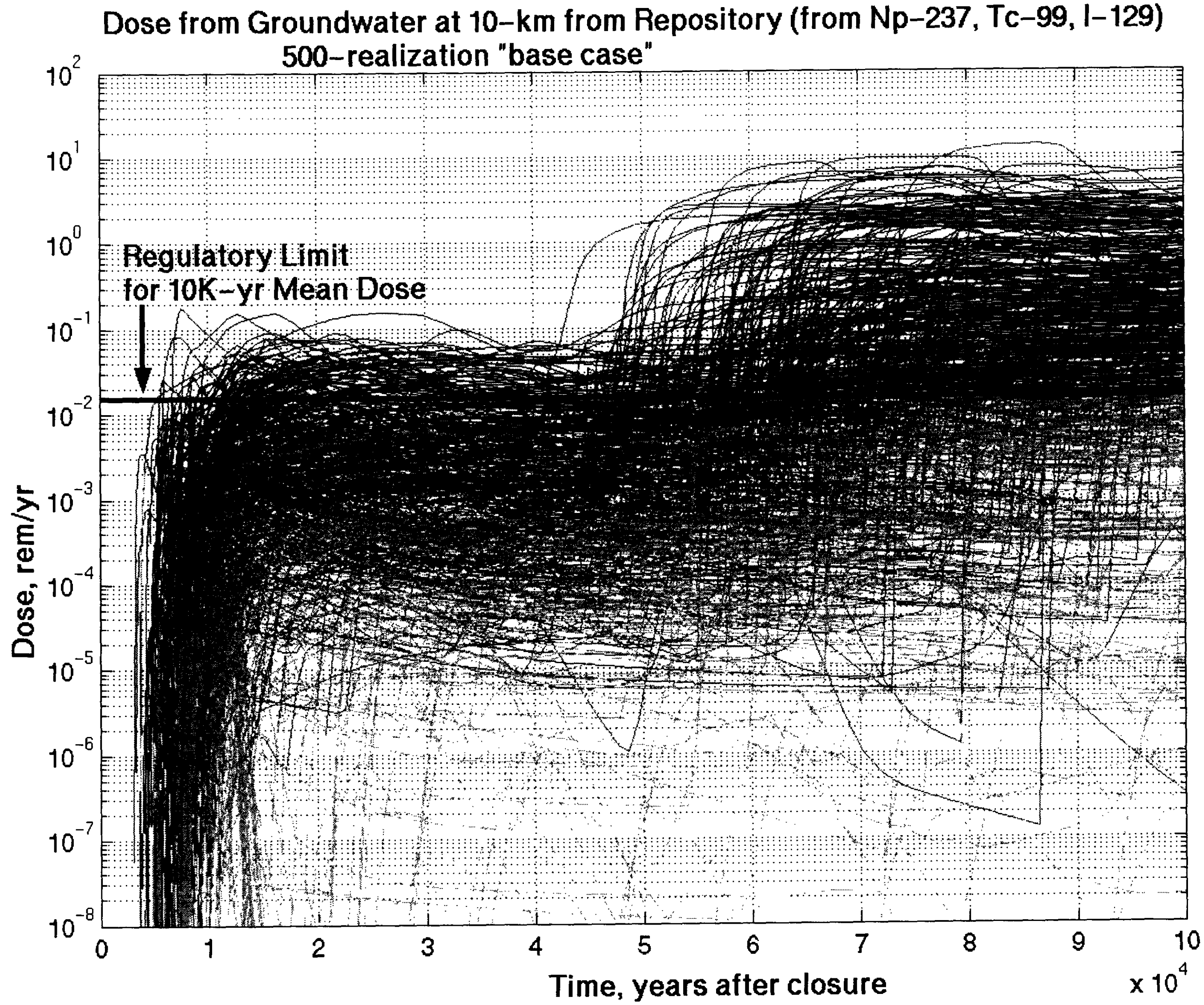

Dose from Groundwater at 10-km from Repository (from Np-237, Tc-99, I-129)
500-realization "base case"
Regulatory Limit
for 10K-yr Mean Dose
Dose, rem/yr
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
1
2
3
4
5
6
7
8
9
10
x 10^4
Time, years after closure

Figure 4.10

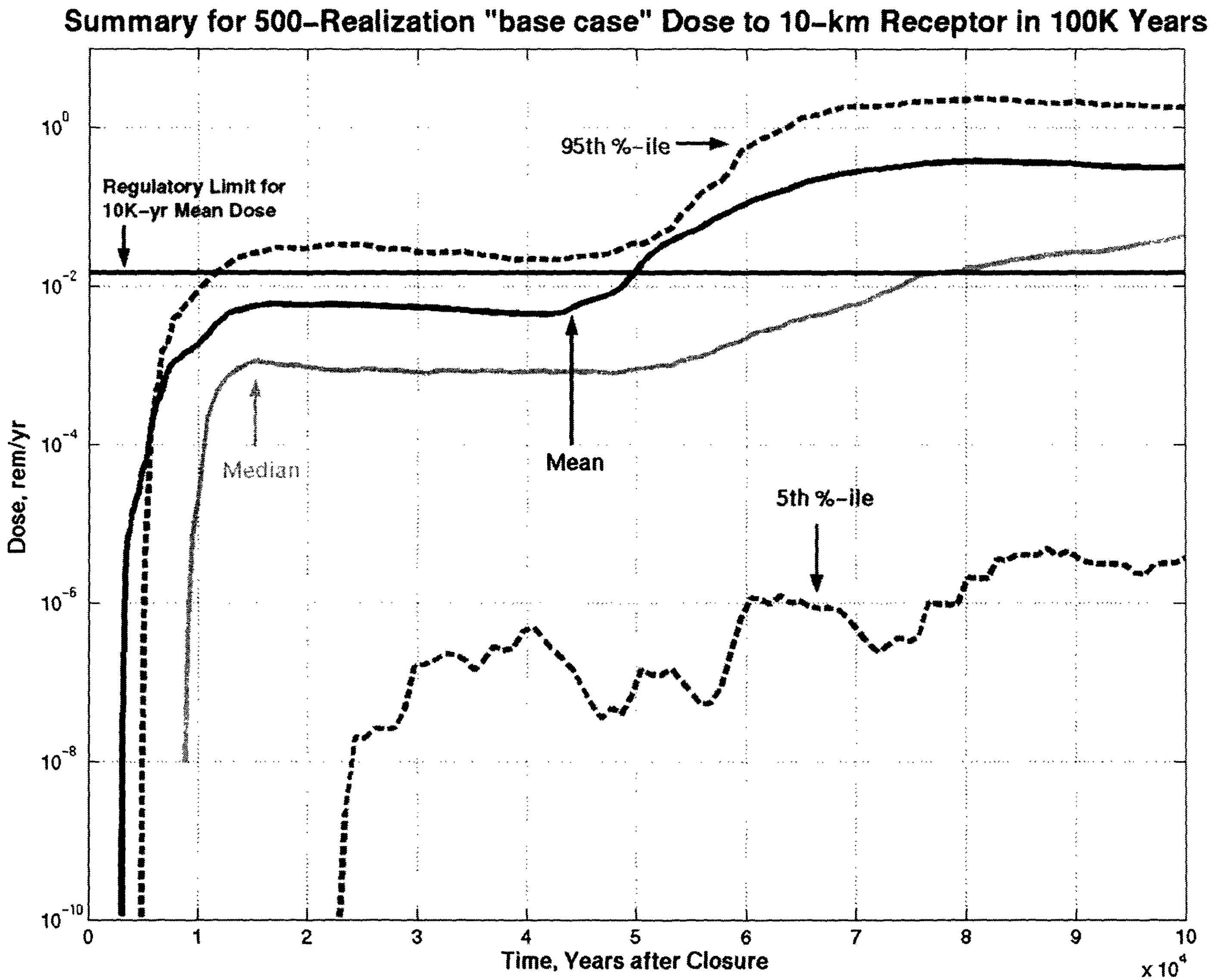
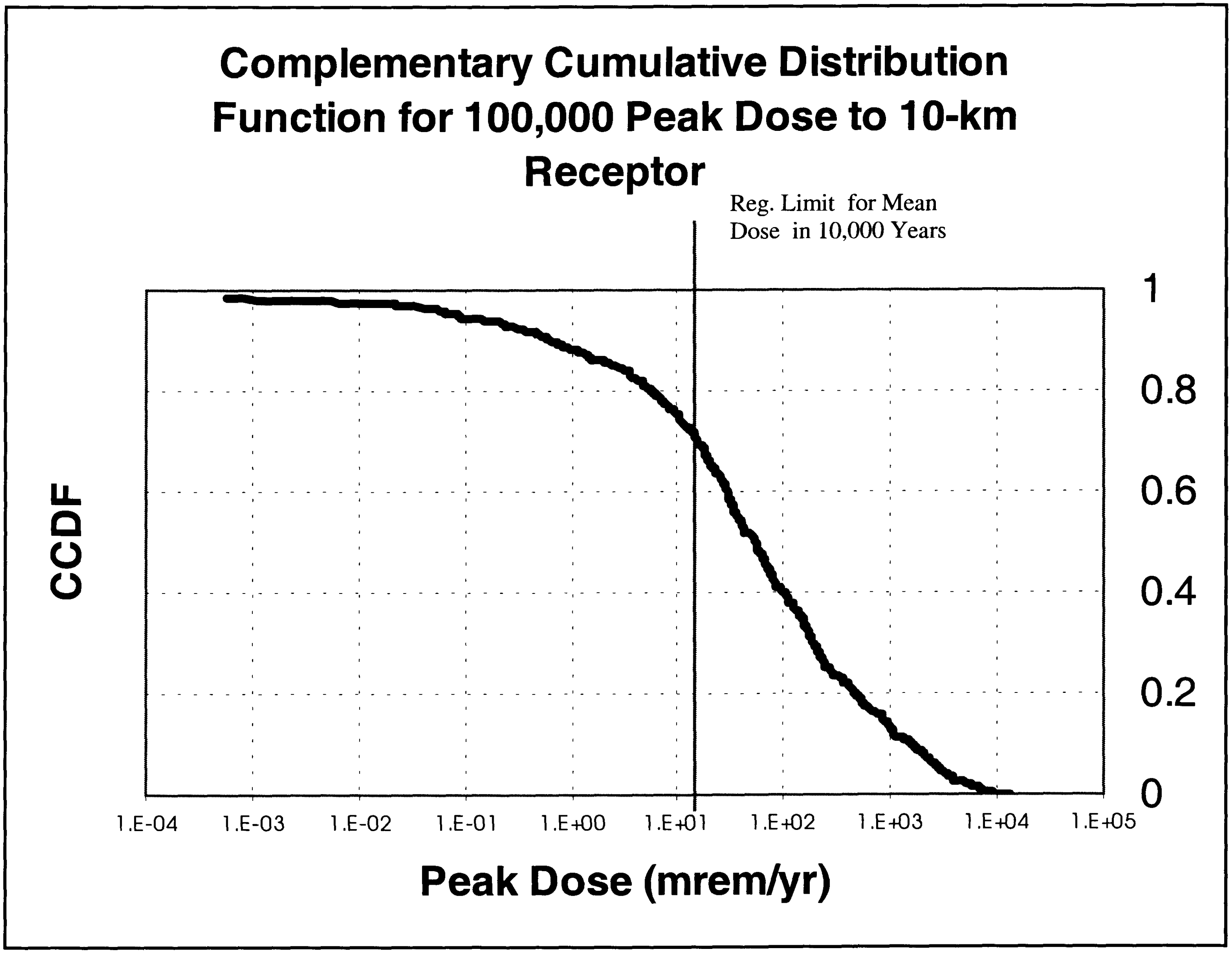
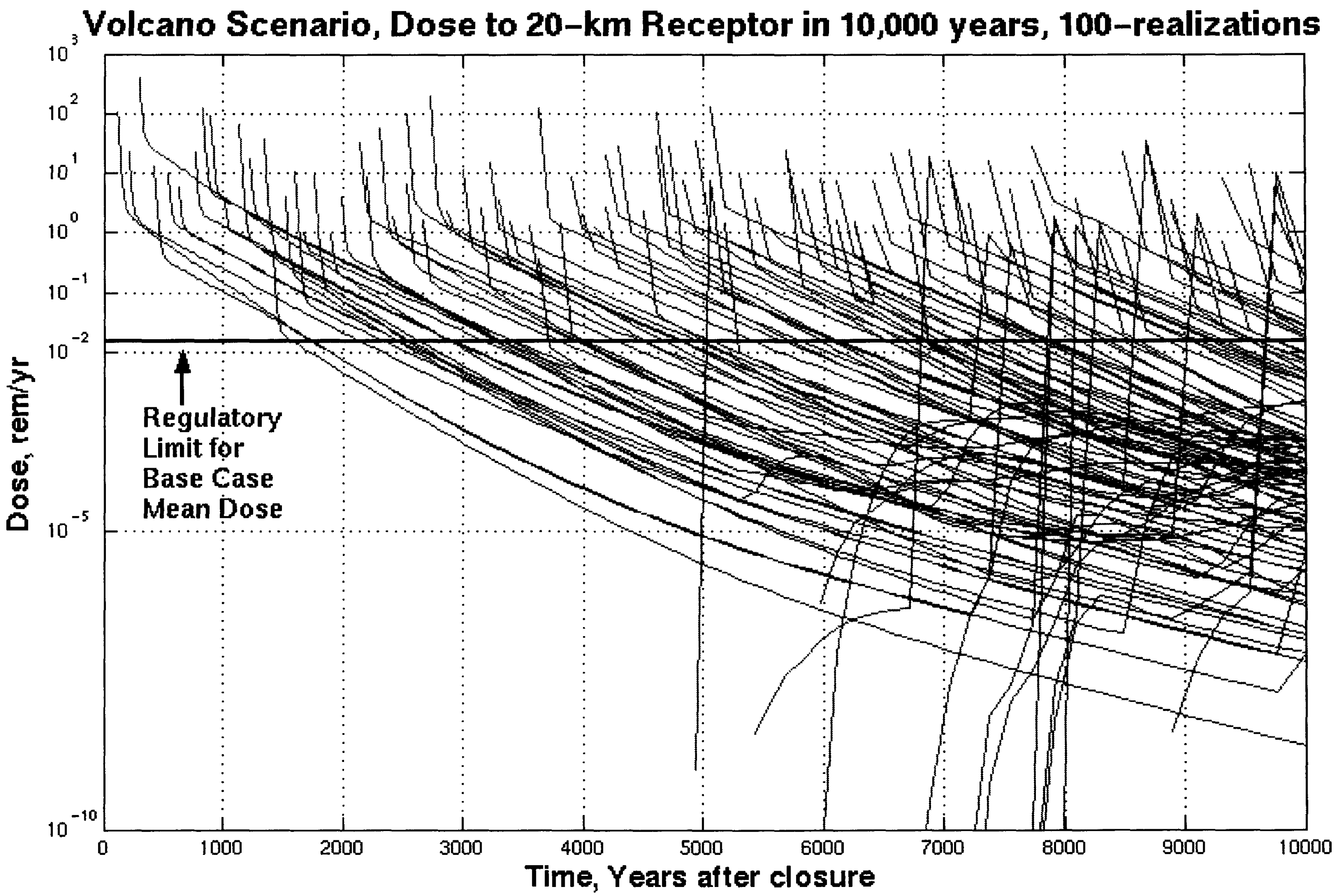

Summary for 500-Realization "base case" Dose to 10-km Receptor in 100K Years
Regulatory Limit for
10K-yr Mean Dose
95th %-ile
Mean
Median
5th %-ile
Dose, rem/yr
Time, Years after Closure
x 10^4

Figure 4.11



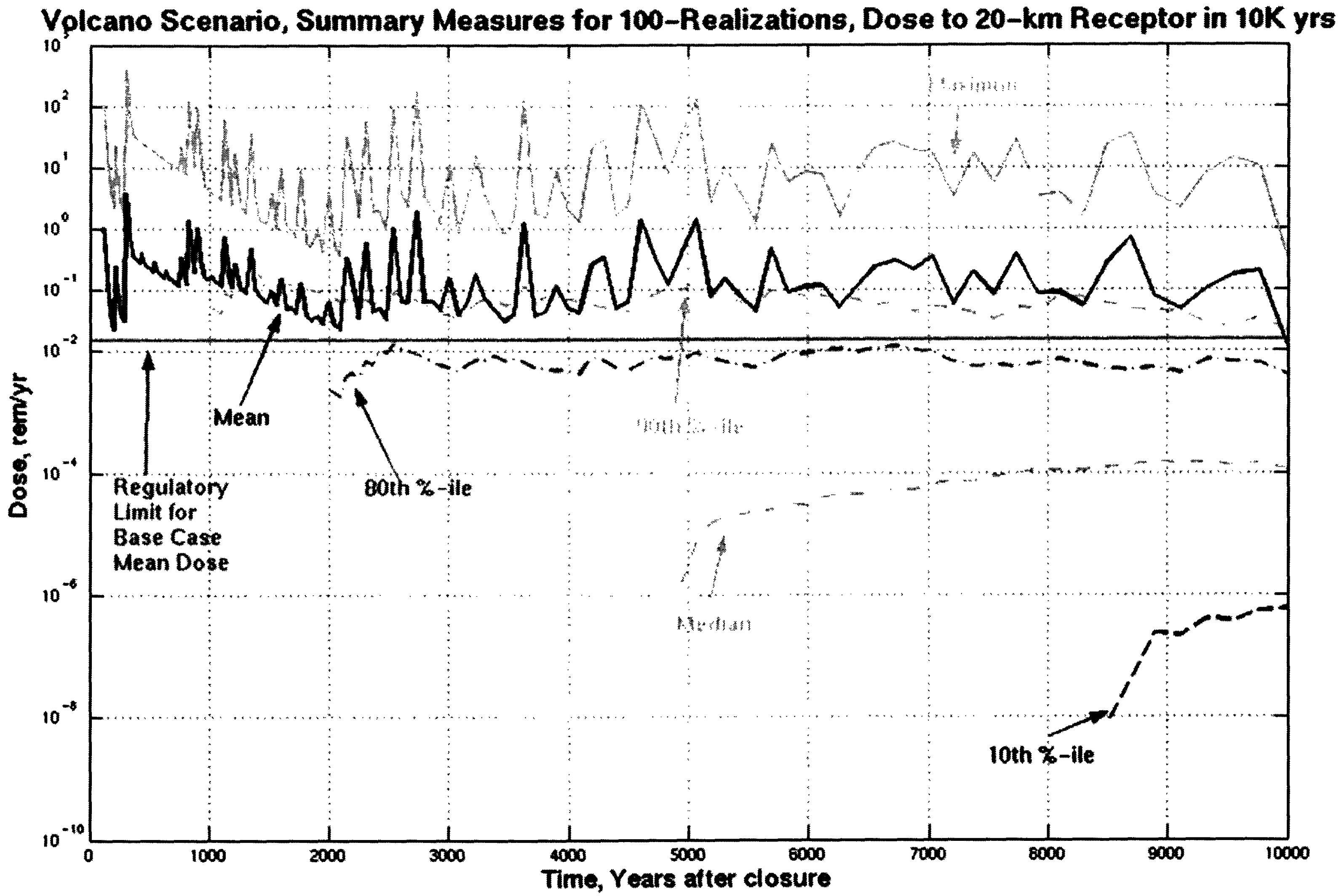
Complementary Cumulative Distribution Function for 100,000 Peak Dose to 10-km Receptor
Reg. Limit for Mean Dose in 10,000 Years
CCDF
1
0.8
0.6
0.4
0.2
0
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
Peak Dose (mrem/yr)

Figure 4.12



Volcano Scenario, Dose to 20-km Receptor in 10,000 years, 100-realizations
Dose, rem/yr
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-5
10^-10
Regulatory
Limit for
Base Case
Mean Dose
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Time, Years after closure

Figure 4.13



Volcano Scenario, Summary Measures for 100-Realizations, Dose to 20-km Receptor in 10K yrs
Dose, rem/yr
Time, Years after closure
Mean
Regulatory
Limit for
Base Case
Mean Dose
80th %-ile
10th %-ile

Figure 4.14

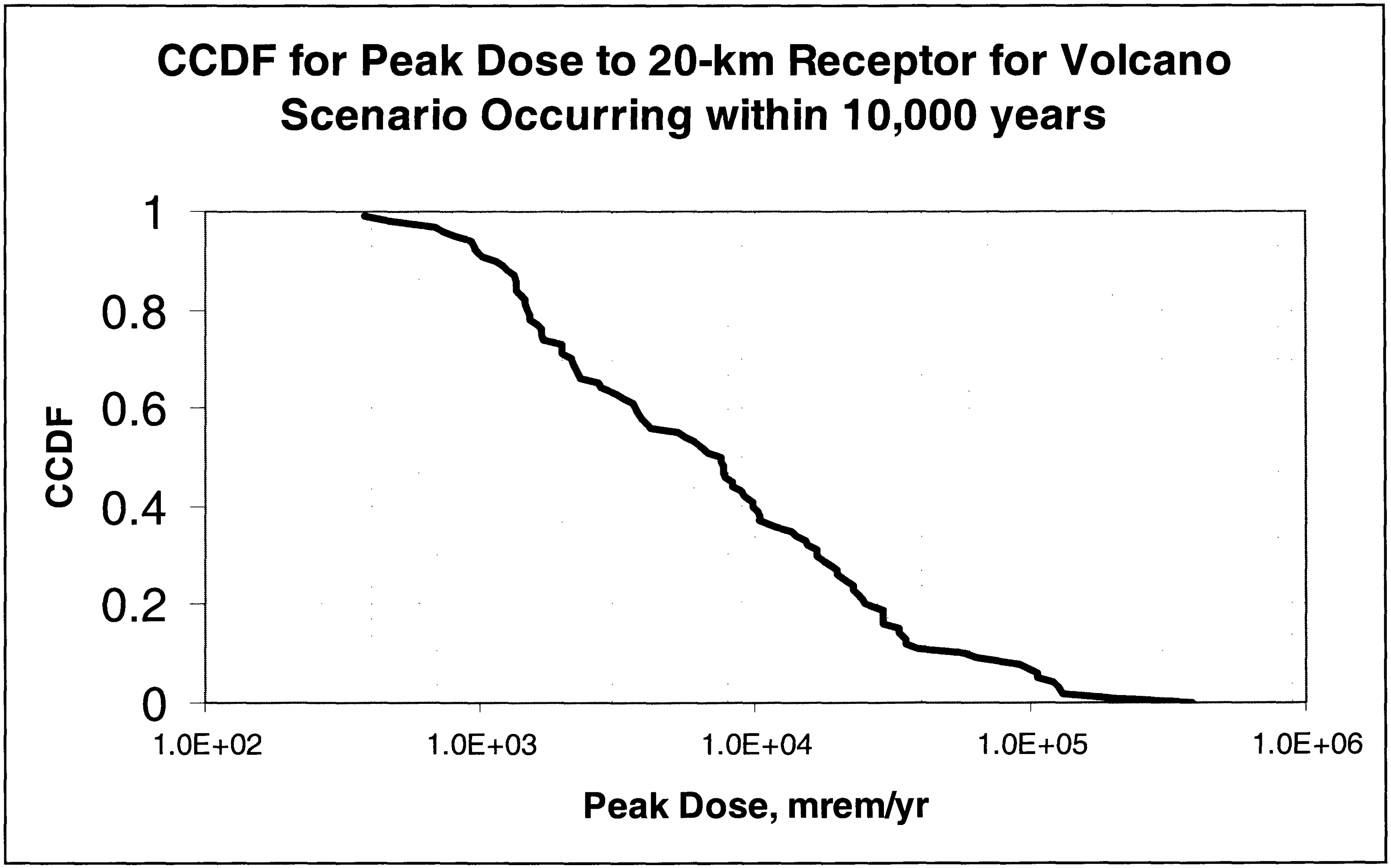

CCDF for Peak Dose to 20-km Receptor for Volcano Scenario Occurring within 10,000 years
CCDF
1
0.8
0.6
0.4
0.2
0
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
Peak Dose, mrem/yr

Figure 4.15

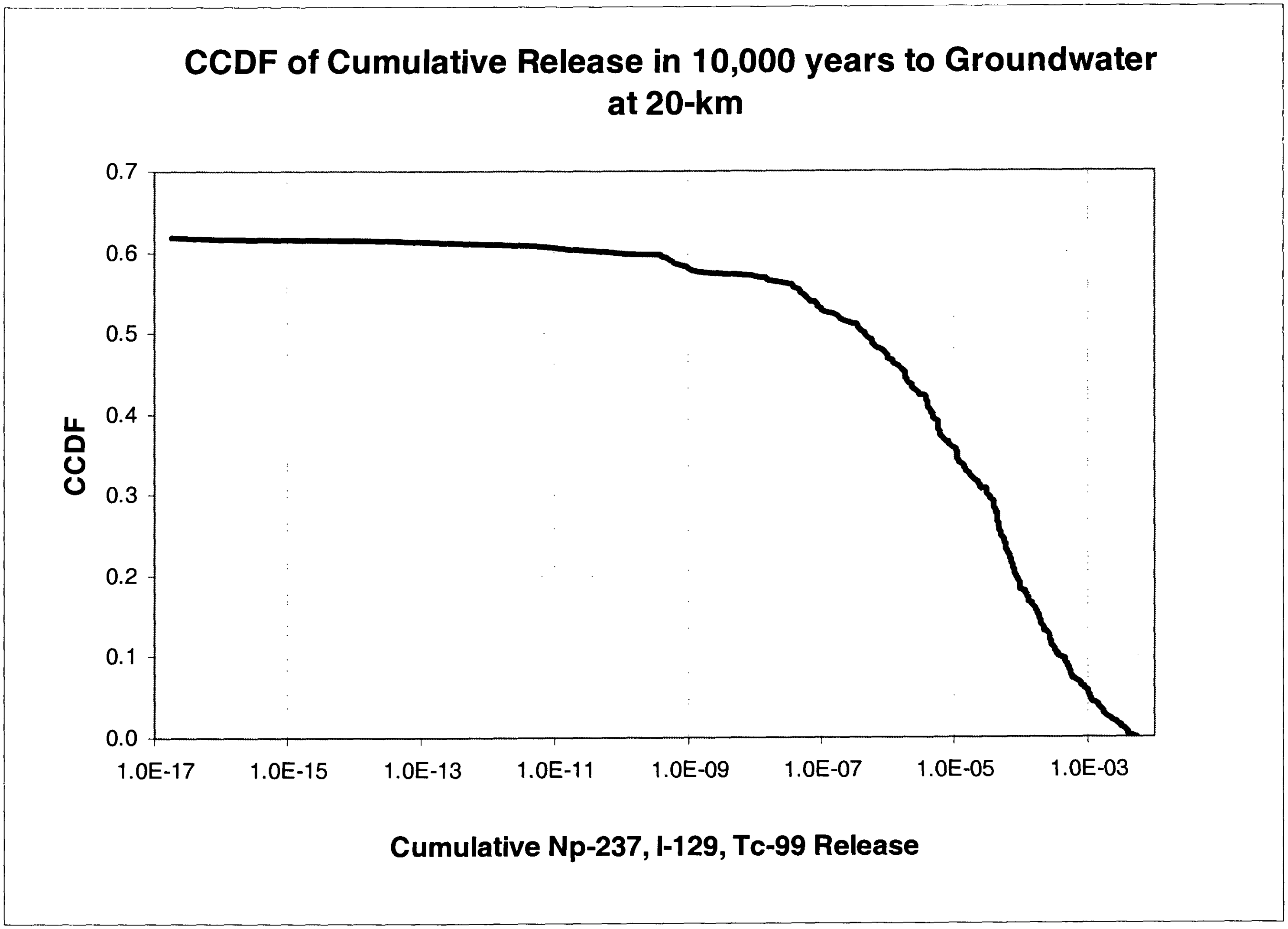
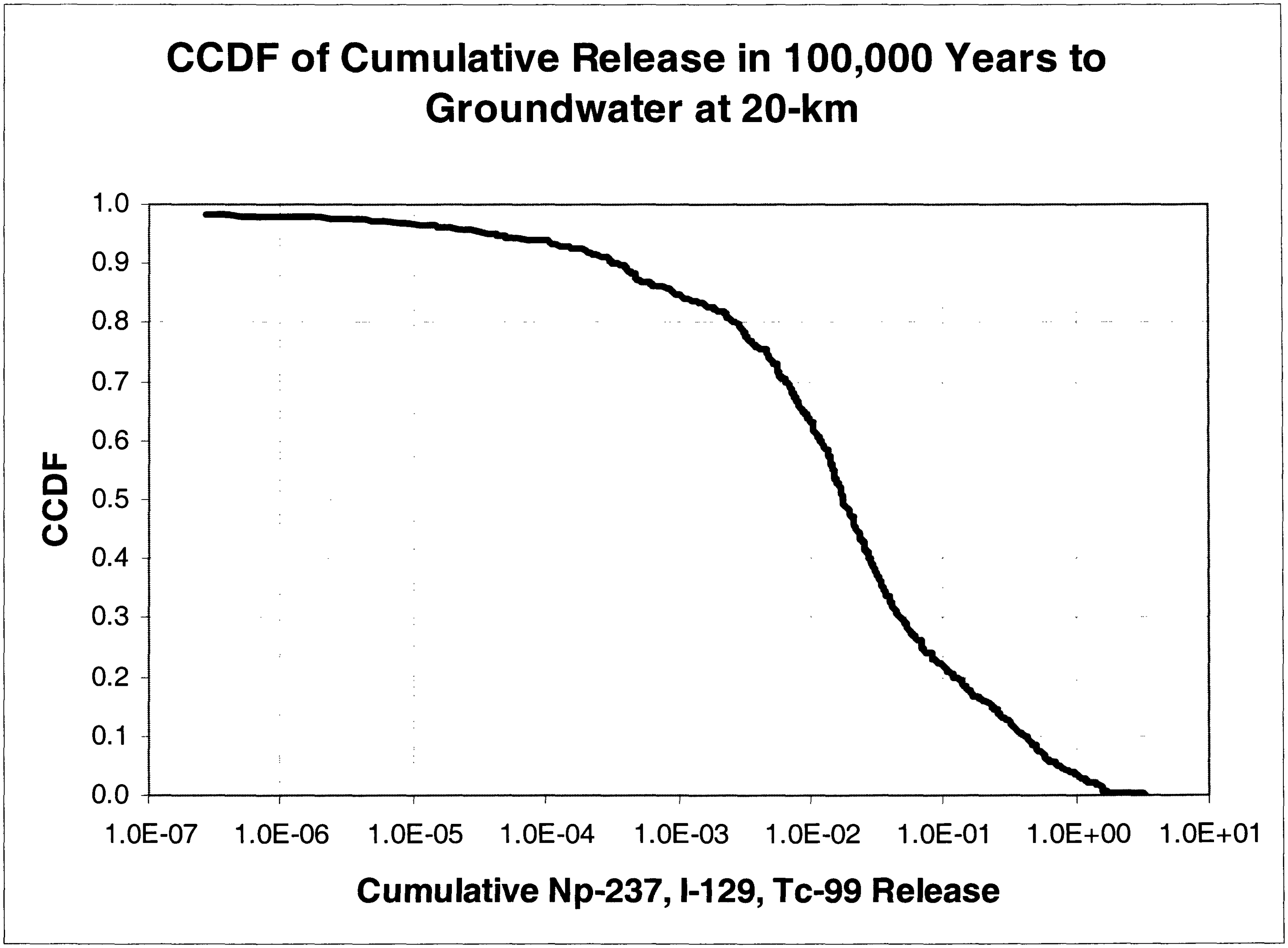

CCDF of Cumulative Release in 10,000 years to Groundwater at 20-km
CCDF
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.0E-17
1.0E-15
1.0E-13
1.0E-11
1.0E-09
1.0E-07
1.0E-05
1.0E-03
Cumulative Np-237, I-129, Tc-99 Release

Figure 4.16



CCDF of Cumulative Release in 100,000 Years to Groundwater at 20-km
CCDF
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
Cumulative Np-237, I-129, Tc-99 Release

Figure 4.17

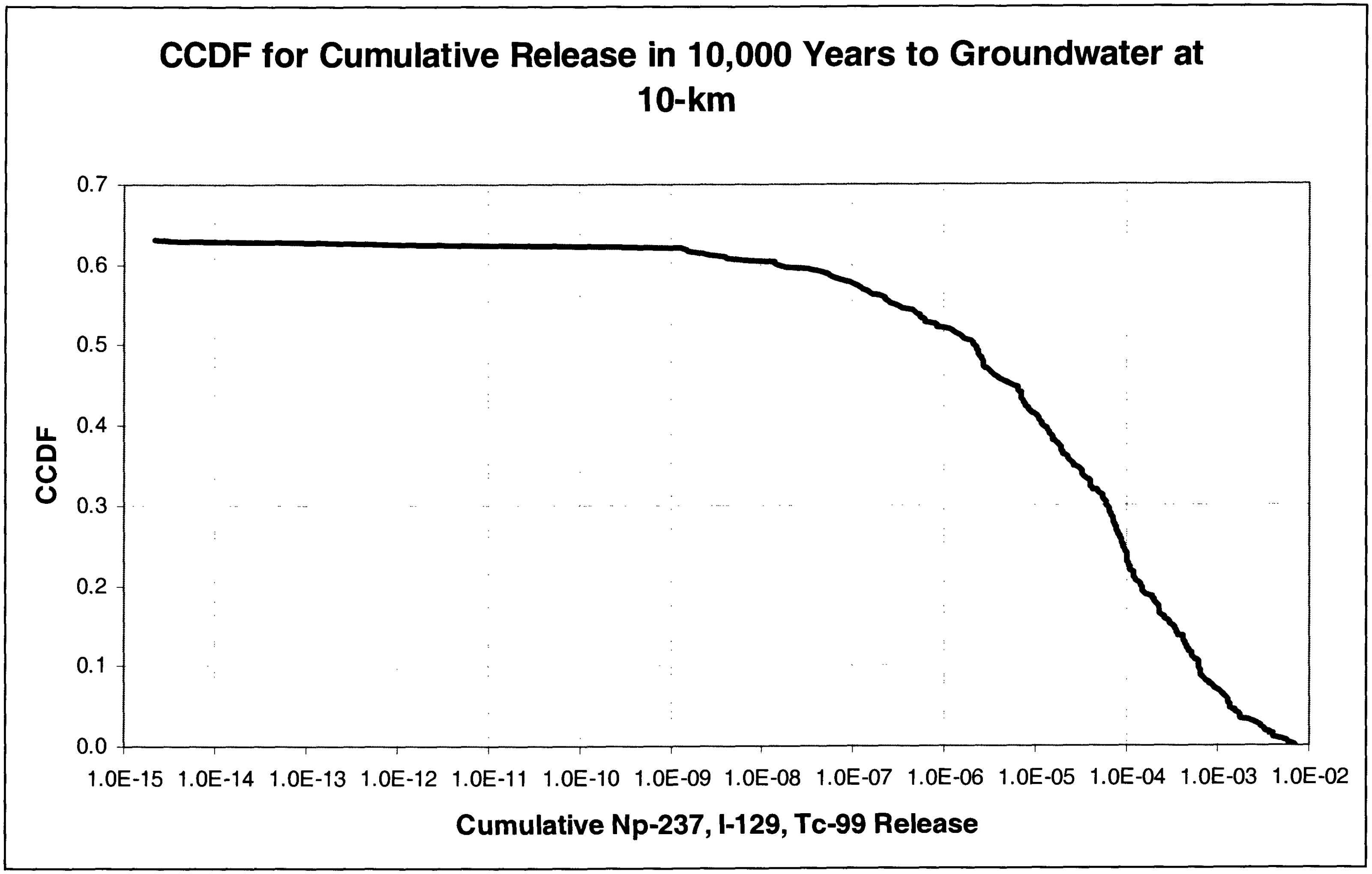
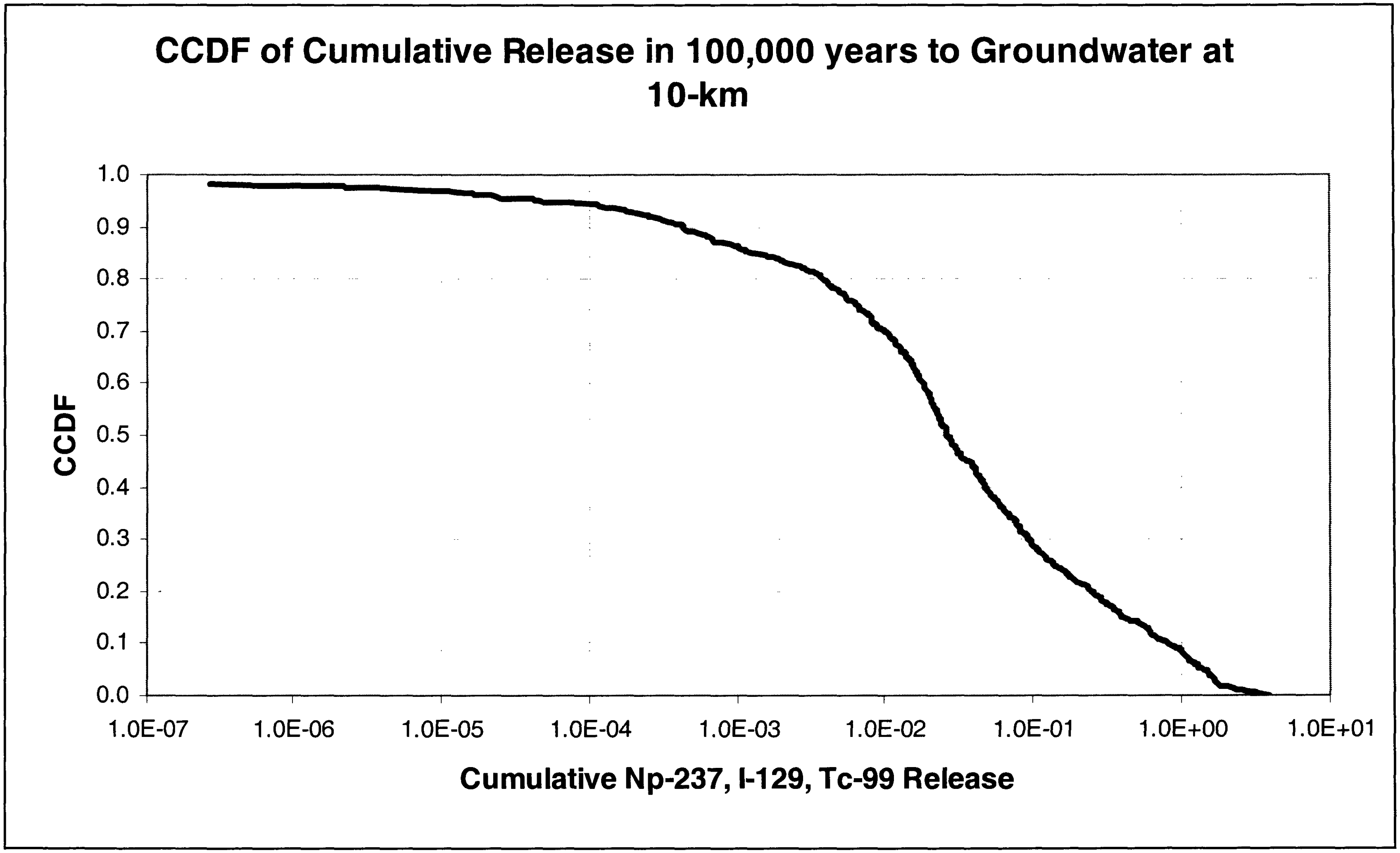

CCDF for Cumulative Release in 10,000 Years to Groundwater at 10-km
CCDF
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.0E-15 1.0E-14 1.0E-13 1.0E-12 1.0E-11 1.0E-10 1.0E-09 1.0E-08 1.0E-07 1.0E-06 1.0E-05 1.0E-04 1.0E-03 1.0E-02
Cumulative Np-237, I-129, Tc-99 Release

Figure 4.18


CCDF of Cumulative Release in 100,000 years to Groundwater at 10-km
CCDF
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
Cumulative Np-237, I-129, Tc-99 Release

Chapter 5 Defense-in-Depth in Risk-Informed Integrated Decision-Making

5.1 Definition and Role of Defense-in-Depth in Risk Management

Before the advent of sophisticated probabilistic risk assessment (PRA) methods, the nuclear industry's approach to safety relied primarily on defense-in-depth in the form of engineered safety margins, redundant safety systems, and multiple physical barriers between the source of hazard and the world outside. As PRA methods have improved, *defense-in-depth* has been re-defined to reflect its role in the context where engineers have better information about the systems they are designing and operating (see [Sorensen et al., 1999] for a more extensive discussion).

The USNRC, as part of its risk-informed performance-based regulatory initiative, developed a regulatory guide (RG 1.174) for nuclear power reactor operators who wished to change their plant-specific licensing basis based on new risk information [USNRC, 2002]. This regulatory guide was the first to propose a way of "risk-informed integrated decision-making" for regulatory matters, i.e., regulatory decisions based on a combination of (a) risk information from PRAs and (b) other important elements such as defense-in-depth and safety margins. The proposed principles of risk-informed integrated decision-making were: "(1) Change meets current regulations unless it is explicitly related to a requested exemption or rule change; (2) Change is consistent with defense-in-depth philosophy; (3) Maintain sufficient safety margins; (4) Proposed increases in CDF or risk are small and are consistent with the Commission's Safety Goal Policy Statement; (5) Use of performance-measurement strategies to monitor the change" [USNRC, 2002]. If we take the rationalist approach to defense-in-depth, which means that anything we do to increase our confidence in a system contributes to defense-in-depth, then principles (2), (3), and (5) are all different facets of defense-in-depth. Taking this into consideration and adapting the RG 1.174 framework for HLW repositories, we propose a framework for risk-informed integrated decision-making for HLW repositories, shown in Figure 5.1. What we have been discussing in the thesis so far is the risk information that can be obtained with PAs. To complement the risk information, we have defense-in-depth and safety margins, quality assurance and control, since this is a key to reducing uncertainty, and the performance confirmation program, which is the pre-or post-closure performance monitoring programs planned in most national HLW repository programs.

In this chapter, we briefly explore how the risk information from PAs, i.e., the risk insights from SPARC analyses, could be used in risk-informed integrated decision-making for HLW repositories. Once again, we will use the YMR for the demonstrative examples.

5.2 Alternative Evaluations of Barrier Capability for Repository Safety Case

5.2.1 Structuralist-Style Defense-in-Depth

In a HLW repository system, the multiple barriers do not act like redundant barriers exactly. The barriers rather act together to keep potential doses low. One of the concerns in evaluating barriers in a repository system is how to consider dependencies among different barriers/repository features. In particular, there are numerous known uncertainties, in the YMR PAs for example, that have been identified as potentially inadequately addressed in existing PAs. In order to determine whether these uncertainties affect multiple barriers, and to get an idea of how the multi-barrier system may be partitioned without losing track of these dependencies, we mapped the most risk-significant "key technical issues" (KTI) identified by the USNRC in its recent YMR risk baseline report [USNRC, 2003]. The influence of these issues on each other, and on different repository barriers, is shown in Figures 5.2, 5.3, and 5.4. One key observation is that in fact, we can separate the issues into three categories: (1) everything leading up to release of the radionuclides from the WP (Figure 5.2); (2) release from the UZ, and (3) release from the SZ. The only connections between the EBS release, UZ release, and SZ release is that the EBS release becomes the source term for the UZ modeling, and the UZ release becomes the source term for the SZ modeling; among the three categories there are no further synergistic effects[35] due to identified uncertainties/incompletenss in the YMR PA. This lends some confidence that most of the key modeling uncertainties in the PA are unlikely to affect multiple categories of barriers, and hence, even after considering the model uncertainties there is significant structural defense-in-depth offered by the current multi-barrier system.

5.2.2 Rationalist-Style Defense-in-Depth

As mentioned in chapter 3, one of the main approaches to assessing barrier capability in the USDOE and USNRC evaluations of the YMR is testing the sensitivity of the PA outcome to the removal or insertion of a barrier. While these evaluations do tell us something about the repository system, this method: (1) does not capture the combined effects of multiple barriers that are slightly degraded, which is more likely to happen; (2) is unrealistic in its assumptions since rarely can an entire barrier (such as "the unsaturated zone") simply disappear, which is what is implied when one removes the barrier in the PA.

The SPARC trees give us another way to assess barrier capability based on risk information. In chapters 3 and 4, we identified repository savior attributes that had a high probability of preventing a substantially-increased-dose (SID) to the dose receptor. The probability of these parameter-assumption ranges being realized is one measure of their potential capability as a barrier against SIDs. Just as we redefined scenarios as collections of assumption

[35] Excluding disruptive events that can affect multiple barriers at once.

ranges (rather than collections of sequential events), here we propose to redefine a barrier as a set of physical properties and/or processes[36] that act in concert to prevent SIDs.

Instead of looking at the change in the mean dose produced by removing a barrier, another way to evaluate the capability of a particular barrier is calculate in what percent of the MCS realizations it saves the repository system from SID-producing behavior. This is in keeping with the main idea in the thesis that instead of looking at (1) general sensitivity and (2) expected outcomes (in projected dose) alone, we should consider the context for the supplementary analyses and concentrate on (1) decision sensitivity, and (2) specific assumption-ranges that produce the undesired outcomes.

For example, if we consider the SPARC tree in Figure 4.7, we see that the preexponential spent fuel dissolution term (PSFDM) parameter could prevent SIDs for the 20-km dose receptor for 100,000-years, if the true value lies below the median (the first 52% of its assumed distribution). This same parameter could 'save' the 10-km receptor from SIDs in 10,000 years, even for the extreme challenge scenario shown in Figure 3.10, if the true value lies in the first 26% of its distribution. These insights indicate that the spent fuel matrix, the waste form, is potentially a very effective barrier. And furthermore, instead of just stating the general importance of this barrier, we can propose that increasing the confidence that the true dissolution rate lies specifically in the first quarter or half of its distribution would greatly increase our confidence in the repository system.

Of course the SPARC results, since they rely on existing PAs, are conditional on many assumptions that are embedded in the PA that we have not discussed explicitly. In particular, there is model uncertainty (as discussed in chapter 2), not all of which is readily explored through the existing PAs, since the PAs don't have built-in options to explore the implications of all the alternate models available for sub-systems. The SPARC trees show which assumption-ranges are

[36] The USDOE and USNRC also discusses "processes" as potential barriers, the only different here is that we consider a set of multiple physical properties and processes at once. Of course ultimately it is somewhat arbitrary what constitutes a single property/process versus multiple properties/processes.

significant, and we can scrutinize the supporting evidence for the assumption-ranges to build more confidence in the assessment. This would correspond to the fourth step of the overall approach presented in chapter 3, "Present supporting evidence for assessing very low probabilities of SID scenarios and probe possible incompleteness." The next section will present a way to do this.

5.3 Decomposing Risk Assessments into Supporting Data and Evidence

In PAs, ultimately all of the distributions that are assigned to parameters are collections of expert judgments. Some people make a strong distinction between distributions based on "data" and/or "evidence", versus those based on "expert judgment," but this is an artificial distinction to some extent. Since there is no operating data for HLW repositories for hundreds of thousands of years, all the distributions involve expert inference from available data that is relevant to repository performance. Two scholars [Clemen and Winkler, 1993] proposed using influence diagrams to visually depict the supporting data and factors influencing experts' judgments about the distribution of an uncertain parameter. This is a good way to look at the supporting evidence for different assumption ranges, step four of the SPARC method. As an example, Figure 5.5 shows the factors influencing the distribution of water percolation flux at the repository horizon. The USDOE completed a formal expert elicitation to assess the distribution of the percolation flux [USDOE, 1997]. As part of the formal process, subject-matter experts with knowledge relevant to estimating the percolation flux presented their insights to the experts in a series of workshops. Part of the goal of these presentations is to ensure that all the experts have some common knowledge base. The USDOE report of the expert elicitation exercise describes all of the major factors of influence, and which expert used which pieces of information, and also how the experts weighed (relatively) the different information. This data on the supporting evidence for experts' quantitative assessment was qualitative. We have compiled the descriptive information in the report into an influence diagram that depicts the factors influencing each expert's assessments; the width of the arrows is a rough indicator of how heavily the expert said he considered the information when formulating his distribution for the parameter. As can be seen in Figure 5.5, although all seven experts were presented with the same evidence in the elicitation workshops, each expert used a different set of information in his assessment and arrived at a different distribution. For example, experts Pruess and Stephens used only present-day net infiltration rate of precipitation in the construction of the percolation flux probability density function (pdf); and while both experts used only this information, Pruess' inference of the implication of infiltration data for percolation flux led to a distribution of higher values than Stephens', i.e., a mean of 11.3 versus 3.9 mm/yr and a 95th percentile of 40 versus 10 mm/yr. This shows disagreement in inference from the same data. Meanwhile, expert Weeks thought the most relevant factors for estimating the percolation flux is evidence of perched water, temperature gradients in the UZ, and radiocarbon gas data; Weeks did not use the net surface infiltration data directly at all. Weeks assessed pdf lies between Pruess' and Stephens' in terms of both mean (7.4 mm/yr) and spread (5th percentile of 1.0 mm/yr and 95th percentile of 21.7 mm/yr). We can see similar differences in the other experts' use of existing data and their inferred pdf's for percolation flux[37]. These differences reflect disagreement among the experts on which factors are most relevant and/or of highest quality in terms of information, for assessing the parameter distribution. The diagram also shows the areas of agreement, e.g., most of the experts (5 out of 7) thought the net surface water infiltration rate ("net infiltration") was an important factor for estimating the percolation flux at the repository horizon.

We can use this additional information in our risk-informed integrated decision-making framework of Figure 5.1. So for example, we know that water is the main vehicle for radionuclides to travel from the YMR to potential dose-receptors in the future, and more specifically, through our SPARC analyses, we know what ranges of infiltration rates and waste-

[37] See [USDOE, 1997] for more details on the elicitation exercise and supporting data.

package flow factors taken together create a difficult challenge for the repository system, or save the repository system. We can combine this information with the decomposition of the experts' assessed parameter distribution ranges, as shown in Figure 5.5, to develop a confidence-building plan. The risk information from the SPARC analyses is the first element in the decision-making framework; and scrutinizing the underlying databases for the SID-producing assumption ranges (or SID-saving assumption-ranges) provides rationalist-style defense-in-depth and quality assurance that the probabilities of the challenges are as low as assessed, or conversely that the probabilities of the savior assumption-ranges are at least as high as assessed. In this way, we can gain a higher level of comfort with the incompleteness in the analyses, i.e., by explicitly scrutinizing important risk contributors and savior attributes and uncover incompleteness.

5.4 Discussion

The SPARC analyses can help evaluate repository barrier capability from a different perspective. In particular, compared to methods currently employed, the SPARC method is able to capture the combined effects of multiple barriers that are slightly degraded, and highlight areas of incompleteness. As such, it forms the basis of an alternate method of barrier capability analysis that can help build confidence in the repository system. The analysis can help identify structural defense-in-depth aspects of the repository system with respect to model uncertainties, and the analysis itself provides defense-in-depth from the rationalist approach.

Figure 5.1 Risk-Informed Integrated Decision-Making Framework (adapted from USNRC RG 1.174)

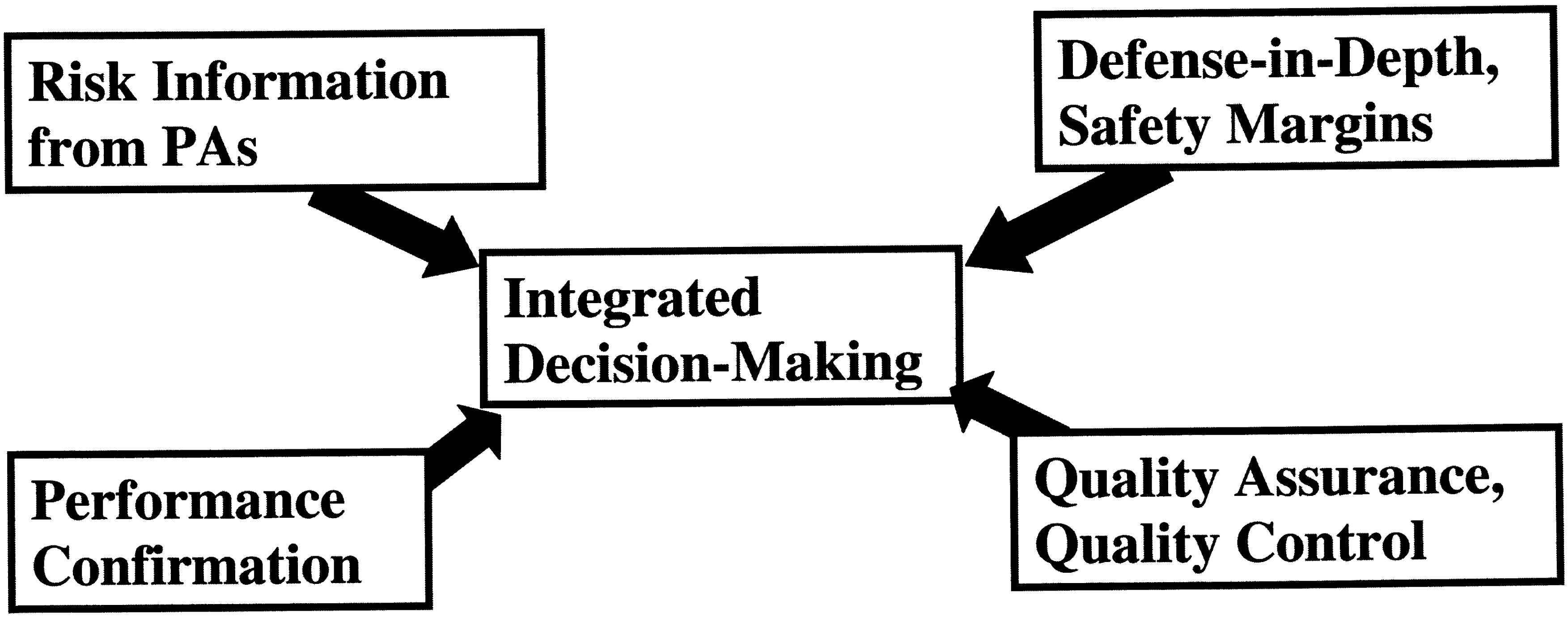


Figure 5.2 Influence Diagram of KTIs Affecting Np-237 Release from EBS

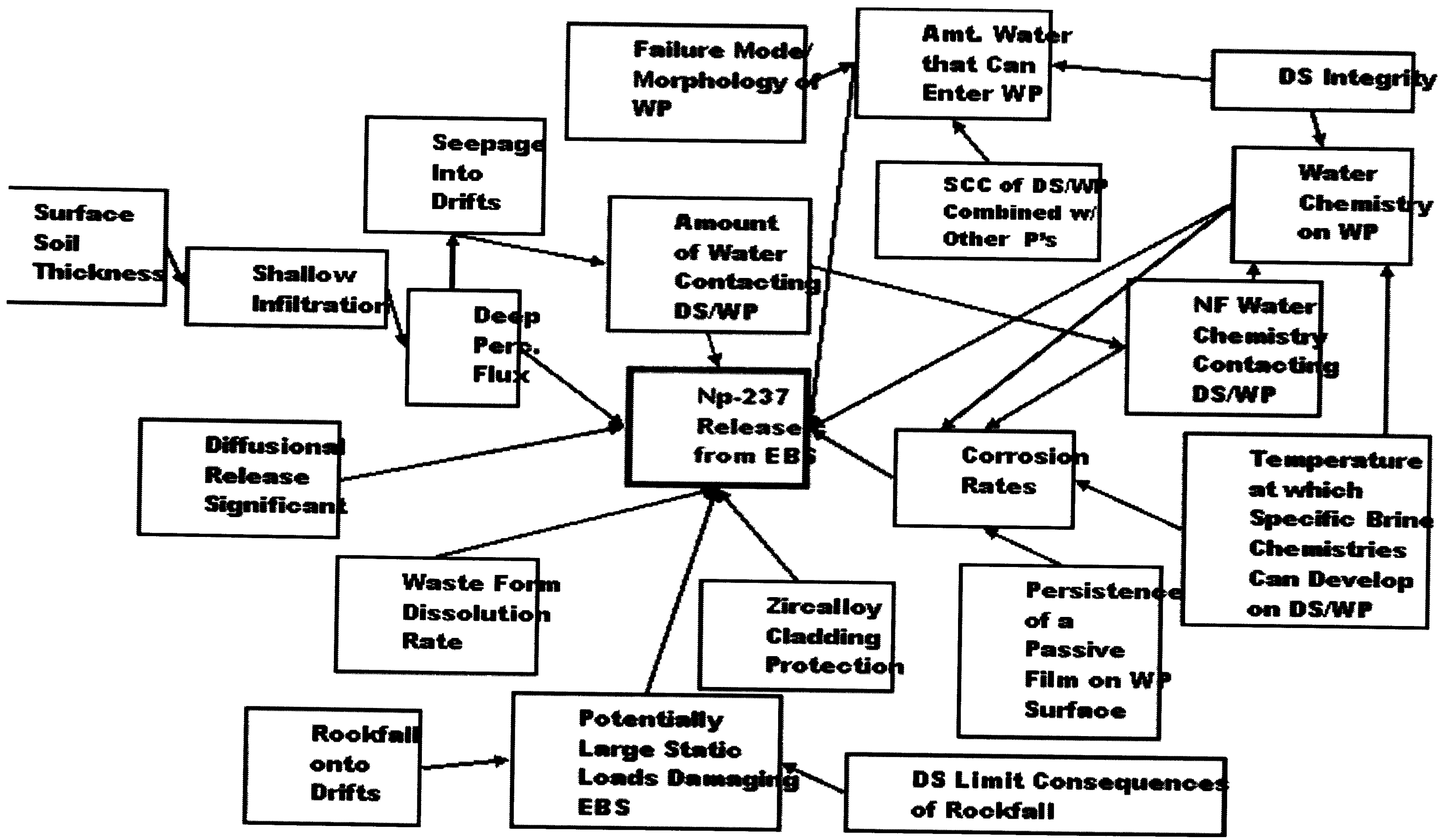


Figure 5.3 Influence Diagram of KTIs Affecting Np-237 Release from the UZ

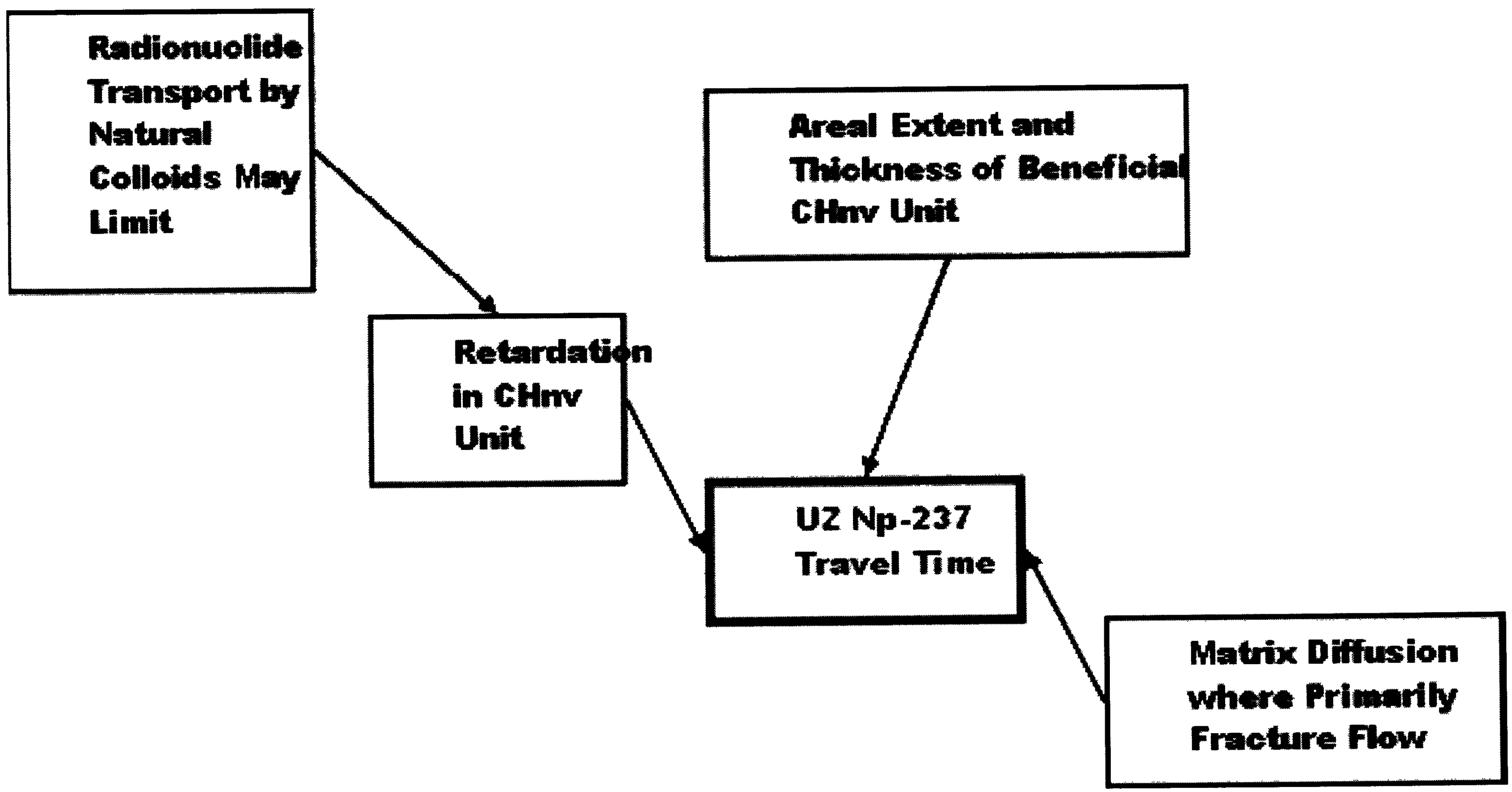


Figure 5.4 Influence Diagram of KTIs Affecting Np-237 Release from the SZ

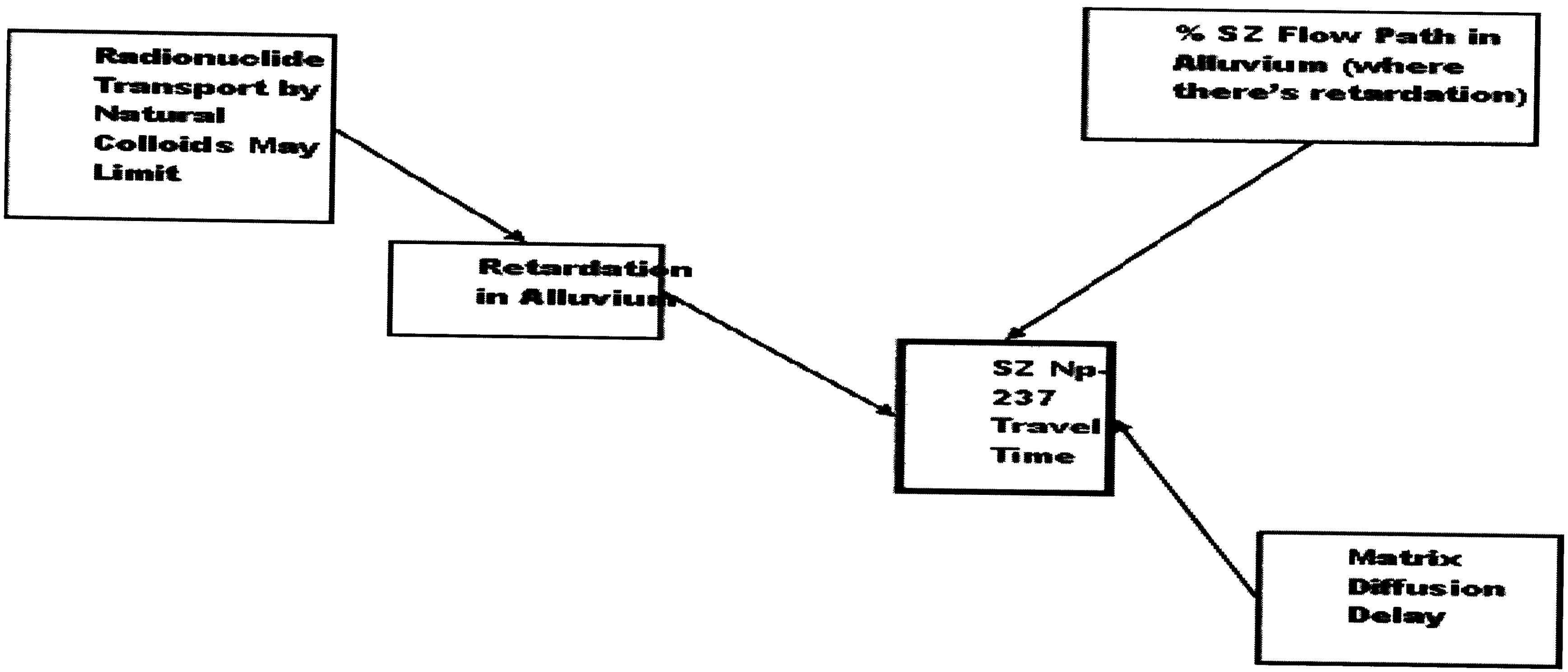
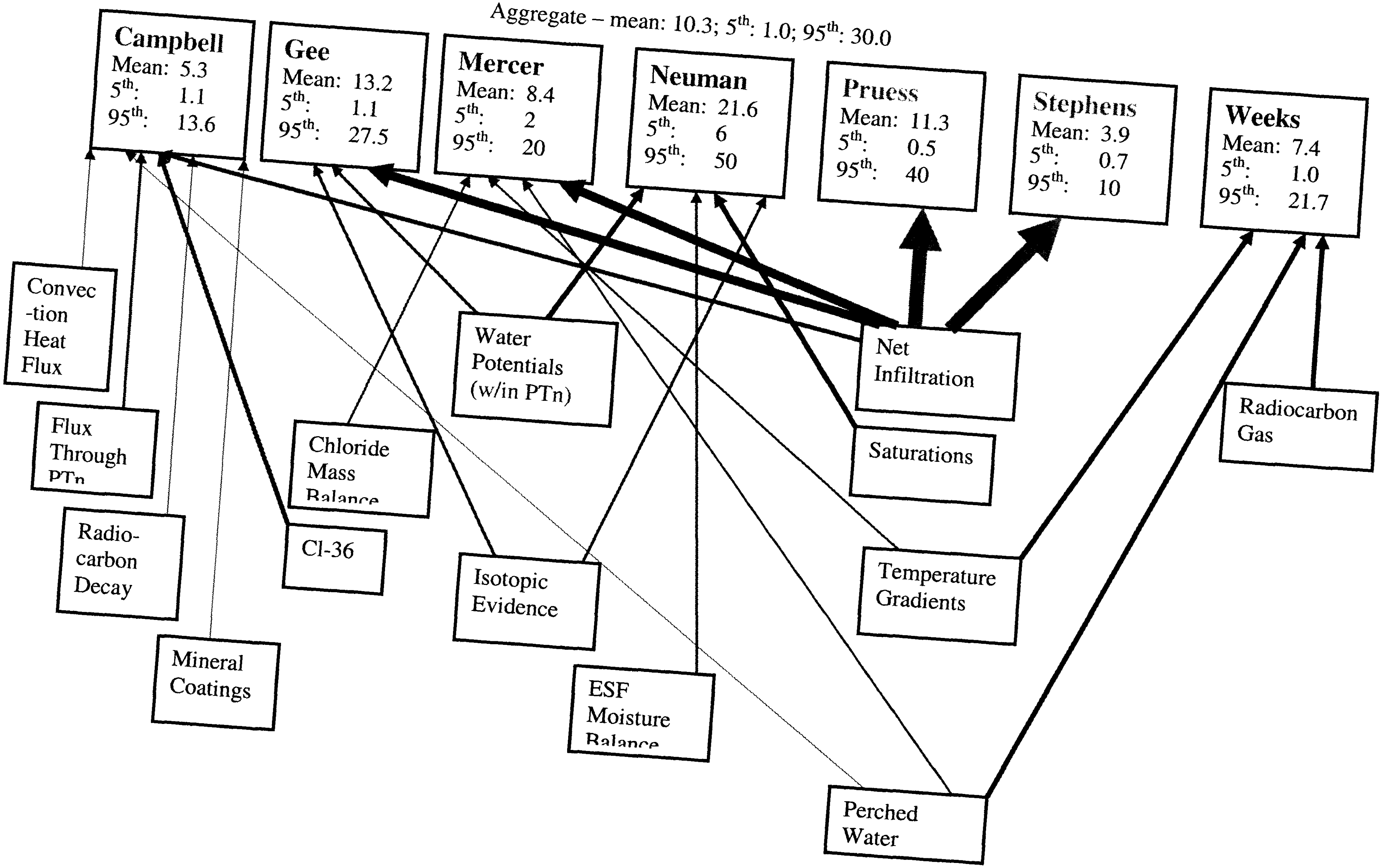


Figure 5.5 Decomposition of UZFM Experts' Estimation of Percolation Flux (mm/yr)
(Based on information in [USDOE, 1997])

Aggregate – mean: 10.3; 5^{th}: 1.0; 95^{th}: 30.0



Chapter 6. Conclusions

The purpose of this thesis is to propose a method for extracting relevant risk information from performance assessments (PAs) for HLW repositories, and to demonstrate the application and usefulness of the method. The Strategic Partitioning of Assumption-Ranges and Consequences method extracts risk information from existing PAs and displays what sets of model parameter values taken together could result in a substantially-increased-dose (SID) from a HLW repository, and what repository attributes, defined in terms of parameter-assumption ranges, have a high worth as savior attributes that prevent SIDs even in challenging situations.

The contributions of this thesis are the following:

1. The thesis develops the SPARC method which provides new information that is not available from other analyses currently used for HLW repositories. The SPARC method explicitly constructs SID-producing scenarios by identifying the uncertain parameter-assumption space that has a very high probability of resulting in SIDs or preventing SIDs (savior attributes). While other sensitivity and uncertainty analysis methods identify parameters that are *generally* important at the total-system level, the SPARC method identifies the *specific* combined distribution-intervals of these important parameters and assumptions that produce or prevent SIDs.
2. The application of the SPARC method to the Yucca Mountain HLW Repository (YMR) has produced interesting insights about savior attributes for the YMR. The most notable of these is that if the uncertainty in one of the key terms in the spent-fuel dissolution model could be bounded to the lower-half or lowest quartile of its current distribution, the confidence in the repository's ability to prevent SIDs would be greatly enhanced; for both preventing doses in excess of 100 mrem/yr produced at 20-km within the first 100,000 years, as well as the doses in excess of 15 mrem/yr produced at 10-km within the first 10,000 years for even extreme

scenarios. Current analyses are focused on studying waste package (WP) corrosion. While WP corrosion is also very important, the SPARC results show that if the true spent fuel dissolution is below the median (for the 20-km, 100 mrem/yr partition case) or in the bottom 25% of its distribution (for the 10-km, 15 mrem/yr partition case for extreme scenarios), the repository could tolerate even the highest corrosion rates assumed to be possible in the NRC's TPA 4.1j code.

3. The SPARC method provides a template for supplementary risk and sensitivity analyses that could be a valuable part of the *safety case* presented by a HLW repository developer. The SPARC analyses can contribute to confidence-building and hence defense-in-depth by providing risk information that is more useful to prioritizing resources spent on further studies into model uncertainty, incompleteness, and the demonstration of the low probability of SID-producing scenarios, since it identifies the most important (strategic) uncertainty partitions, offers alternate evaluations of barrier capability, and is flexible enough to address a wide array of stakeholder concerns in the public risk discourse on HLW repositories.

Although the SPARC method was developed for and has been applied in this thesis to HLW repositories, it is flexible enough to be useful in a variety of societal risk decisions and discourse. It is particularly well-suited for systems that are partly engineered and partly existing in the natural environment, where binary-failure modeling is not adequate; for example, decisions on environmental contamination at USDOE facilities or hazardous waste disposal could benefit from SPARC analyses.

NOMENCLATURE

ACNW	USNRC's Advisory Committee on Nuclear Waste
ACRS	USNRC's Advisory Committee on Reactor Safeguards
CDF	Cumulative distribution function
CCDF	Complementary cumulative distribution function
CFR	Code of Federal Regulations
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPRI	Electric Power Research Institute
F(x)	Cumulative distribution function for the variable, x
FOCTR	Fraction of Condensate moving Toward Repository
GSA	Generalized sensitivity analysis
HLW	High-level radioactive waste
HTOM	High-temperature operating mode
IAEA	International Atomic Energy Agency
INEL	Idaho National Engineering and Environmental Laboratory
IRT	International Review Team
IWPD	Initial waste package defect rate, TPA 4.1 parameter WPDef%
K_d	Sorption coefficient
KTI	Key Technical Issue
LHS	Latin hypercube sampling
LLNL	Lawrence Livermore National Laboratory
MCS	Monte Carlo simulation
MOW	Model of the World
NAS	US National Academy of Science
NEA	Organization for Economic Cooperation and Development's Nuclear Energy Agency
NRC	US National Research Council
NTS	Nevada Test Site
NWPO	Nevada Nuclear Waste Project Office
NWTRB	Nuclear Waste Technical Review Board
PA	Performance assessment
pdf	Probability density function
PRA	Probabilistic risk assessment
QRA	Quantitative risk assessment
RMEI	Reasonably maximally exposed individual
SA	Sensitivity analysis
SAW%	Subarea wet percent, TPA 4.1 parameter SubAreaWet%
SFD	Pre-exponential term in spent fuel dissolution model, TPA 4.1 parameter PSFDM1
SID	Substantially Increased Dose
SOL	Solubility of Neptunium, TPA 4.1 parameter SolblNp
SPARC	Strategic Partitioning of Assumption-Ranges and Consequences
TSPA	USDOE's total-system performance assessment
TPA	USNRC's total-system performance assessment
TSPA-SR	Total-System Performance Assessment—Site Recommendation
USDOE	US Department of Energy
USEPA	Environmental Protection Agency
USNRC	US Nuclear Regulatory Commission
WIPP	Waste Isolation Pilot Plant (for US transuranic waste)

WPFF	Waste package flow multiplication factor, TPA 4.1 parameter WPFlowMF
WP	Waste package
YM	Yucca Mountain
YMR	Yucca Mountain Repository

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